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THE MECHANISM OF NITROGEN UTILIZATION BY AZOTOBACTER

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The nitrogen molecule is very inactive, and considerable energy is required to make it reactive, since the two atoms in N_2 are combined very strongly. But when the two atoms of nitrogen are separated and combined with other elements they are very active. In an investigation of the mechanism of nitrogen fixation by Azotobacter, the primary question that arises is how the bacteria first combine with the free nitrogen. In answer to this question, many explanations have been given. These may be divided into three main groups, as follows:

The theory of the direct combination of the nitrogen with certain organic compounds in the cells of the bacteria. This is difficult to prove by experiment.

The oxidation theory. This is disproved by the fact that no trace of either nitrite or nitrate has been found in bacteria or in their culture solutions.

The reduction theory. This is supported by the occurrence of an increase, followed by a decrease, of ammonia in some culture solutions of Azotobacter.

Although the decrease of ammonia in culture solutions shows that nitrogen can be absorbed by bacteria in the form of ammonia, this does not prove that the nitrogen is fixed in the form of ammonia, since, for instance, the latter may have been produced from nitrite by reduction. It would, of course, be difficult to detect nitrite if its velocity of production from free nitrogen were slower than that of its transformation to ammonia.

Rossi (5) recently claimed, in accordance with Winogradsky's experimental findings (7), that the first process in nitrogen fixation by Azotobacter is the formation of ammonia. Winogradsky found that much ammonia was produced by Azotobacter in a silica-gel culture containing sodium lactate or succinate instead of mannite, as judged not only by chemical reaction but also by odor.

Wieland (6) explained the production of hydrazine in the fixation of nitrogen by Azotobacter on the basis of his theory of dehydrogenation. He assumed that a certain substance, which exists in bacteria and activates hydrogen, does not facilitate the combination of hydrogen with oxygen, but activates molecular nitrogen to form hydrazine. His experimental results proved the correctness of the oxidation process considered in his report but did not fully prove that of the mechanism of the nitrogen fixation.

A long time ago the senior author and his associates (1, p. 44; 2, p. 128; 4) suggested the formation of ammonium nitrite in nitrogen-fixing bacteria by the combination of one molecule of nitrogen with two molecules of water as follows:

$$N_2 + 2\,H_2O = NH_4NO_2$$

This view was merely an opinion in regard to ammonia formation and was not proved experimentally.

Recently, Burk and Horner (3) reached the conclusion that the extracellular ammonia observed so far, in their own and in previous investigations, is in all probability derived entirely from the decomposition of normal cell nitrogen and not, in any measurable quantity, by direct synthesis from free N_2 by Azotobacter.

Since accurate analytical methods for the determination of nitrogen compounds produced in the bacterial cells or culture solutions are devised with difficulty, we made the following experiments in order to ascertain how the nitrogen in nitrate, nitrite, and ammonia would be utilized by Azotobacter when these compounds were added separately or in combination to culture solutions.

EXPERIMENTAL METHOD

Three strains of Azotobacter were used in our experiments, as follows: *Azotobacter chroococcum*, isolated from a field soil in China; *Azotobacter Beijerinckii*, isolated from the paddy field soil at the Shizuoka Agricultural Experiment Station; and *Azotobacter vinelandii*, isolated from the paddy field at the Miye Agricultural Experiment Station.

A slightly alkaline (pH 7.5) Ashby's culture solution containing the following compounds was used: mannite, 10.0 gm.; NaCl, 0.2 gm.; KH_2PO_4, 0.5 gm.; $CaSO_4$, 0.1 gm.; $MgSO_4$, 0.2 gm.; distilled water 1000 cc. Mobybdenum and iron were not specifically added, and all experiments reported were performed with inorganic nitrogen compounds, KNO_3, $NaNO_2$ (or KNO_2), and $(NH_4)_2SO_4$, added at a concentration of 0.02–0.03 per cent, which is recognized as favorable for the growth of these bacteria.

The fixation of nitrogen by Azotobacter was not observed in such culture solutions containing fixed nitrogen, as table 1 shows. Duplicate 20-cc. portions of Ashby's culture solutions, containing the aforementioned inorganic nitrogen compounds respectively, were put into 100-cc. Erlenmeyer flasks, sterilized for 30 minutes for three successive days in Koch's apparatus, and then inoculated with a pure culture solution of Azotobacter and incubated at 28°–30°C. Each culture solution, after a given time, was diluted to 250 cc. with distilled water and was analyzed for nitrate, nitrite, or ammonia by the usual colorimetric methods (nitrate, with phenoldisulfonic acid; nitrite, with Gries reagents; and ammonia, with Nessler's reagent).

TABLE 1

*Nitrogen in culture solutions**

TIME	A. CHROOCOCCUM			A. VINELANDII		
	NO_3-N	NO_2-N	NH_3-N	NO_3-N	NO_2-N	NH_3-N
days	*mgm.*	*mgm.*	*mgm.*	*mgm.*	*mgm.*	*mgm.*
0	0.85	1.15	0.69	0.85	1.15	0.69
1	0.85	1.15	0.69	0.85	1.15	0.69
2	0.85	1.15	0.69	0.85	1.15	0.69
3	0.85	1.15	0.69	0.85	1.15	0.69
4	0.85	1.15	0.69	0.85	1.15	0.69
5	0.85	1.15	0.69	0.85	1.15	0.69
7	0.90	1.30	0.69	0.90	1.30	0.69
9	0.90	1.30	0.69	0.90	1.30	0.69
12	0.90	1.30	0.69	0.90	1.30	0.69

* 20 cc. of each culture solution was used, to which was added 0.83 mgm. NO_3-N, 1.22 mgm. NO_2-N, or 0.64 mgm. NH_3-N. Incubation at 28°–30°C.

TABLE 2

Production of NH_3-N from NO_3-N by Azotobacter

TIME	A. CHROOCOCCUM*				A. BEIJERINCKII†				A. VINELANDII†			
	NO_3-N disappeared		NO_2-N produced	NH_3-N produced	NO_3-N disappeared		NO_2-N produced	NH_3-N produced	NO_3-N disappeared		NO_2-N produced	NH_3-N produced
days	*per cent*	*mgm.*	*mgm.*	*mgm.*	*per cent*	*mgm.*	*mgm.*	*mgm.*	*per cent*	*mgm.*	*mgm.*	*mgm.*
0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0
1	22	0.12	0.0020	0.01	4	0.03	0.0043	0.02	1	0.01	0.0078	0.02
	15	0.09	0.0016	....	3	0.03	0.0045	0.02	2	0.02	0.0072	....
2	31	0.18	0.0007	0.01	10	0.08	0.0018	0.03	12	0.10	0.0020	0.03
	39	0.17	0.0008	0.02	9	0.08	0.0018	0.03	18	0.15	0.0020	0.03
3	43	0.26	0.0008	0.03	..	....	0.0008	0.04	20	0.17	0.0010	0.03
	37	0.23	0.0008	0.03	..	....	0.0008	0.05	..	....	0.0008	0.03
4	45	0.27	0.0005	0.04	25	0.21	0.0007	0.04	25	0.21	0.0007	0.04
	40	0.24	0.0005	0.04	32	0.27	0.0007	0.04	22	0.19	0.0005	0.04
5	50	0.30	0.0003	0.03	29	0.24	0.0005	0.06	23	0.19	0.0007	0.04
	53	0.32	0.0003	0.04	38	0.31	0.0005	0.06	32	0.27	0.0007	0.04
7	61	0.36	0.0003	0.06	42	0.35	0.0003	0.06	35	0.29	0.0003	0.05
	60	0.36	0.0003	0.07	45	0.37	0.0003	0.06	37	0.31	0.0003	0.05
9	69	0.41	0.0003	0.05	..	....	0.0002	0.10	35	0.29	0.0001	0.04
	76	0.45	0.0003	0.06	..	....	0.0002	0.10	35	0.29	0.0001	0.04
12	76	0.45	.....	0.08	59	0.49	.....	....	40	0.33	.....	....
	78	0.46	.....	0.09	55	0.46	.....	....	..	....	.....	....

* 15 cc. of culture solution containing 4.3 mgm. KNO_3 (0.594 mgm. NO_3-N) was used.
† 20 cc. of culture solution containing 6 mgm. KNO_3 (0.832 mgm. NO_3-N) was used.

EXPERIMENTAL RESULTS

Change of N when each inorganic nitrogen compound is present separately in the culture solution. It is clear from table 2 and from figures 1, 2, and 3, that almost all the NO_2-N disappeared after 5–6 days, NH_3-N after 8–9 days, and NO_3-N still more slowly. In culture solutions containing NO_2-N much NH_3-N was produced, reaching a maximum when all the NO_2-N had disappeared; after this NH_3-N disappeared very rapidly. Where NO_3-N was added, its disappearance was relatively slow, 20 per cent still remaining after 12 days; and the production of NH_3-N was very small. A small quantity of NO_2-N was found in these culture solutions (table 2).

From the foregoing results, it may be deduced that the Azotobacter absorb NH_3-N as their nutrient, and use NO_2-N and NO_3-N after reducing these to ammonia. The accumulation of NH_3-N in the NO_2-N solution indicates

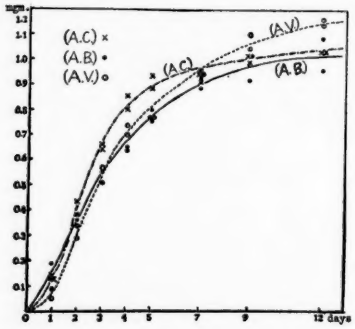

FIG. 1. ABSORPTION OF NH_3-N BY AZOTOBACTER

A.C., A.B., and A.V. = *Azotobacter chroococcum*, *A. Beijerinckii*, and *A. vinelandii*, respectively. Culture solution used: 20 cc. containing 6 mgm. $(NH_4)_2SO_4$ (1.27 mgm. NH_3-N).

that the reduction velocity of NO_2-N to NH_3-N is more rapid than the velocity of absorption of NH_3-N (fig. 2). The reduction velocity of NO_3-N to NO_2-N is apparently much slower than that of NO_2-N to NH_3-N, since only a trace of NO_2-N was detected in the NO_3-N solution.

Change of N when two forms of inorganic nitrogen are present in the culture solutions. Figure 4 shows that Azotobacter absorb NH_3-N after reducing NO_2-N, even in the presence of much NH_3-N as NH_4NO_2.

Figures 1 and 5 show that when equal quantities of NH_3-N are added in the form of sulfate and nitrate, NH_3-N disappears somewhat more rapidly in the former case than in the latter. This result was apparently due not to the direct influences of the SO_4 and the NO_3 ions, but to the consumption of NO_3-N (presumably via reduction to NH_3-N). In this connection, table 3 shows that the sum of NH_3-N and NO_3-N of NH_4NO_3 disappeared is

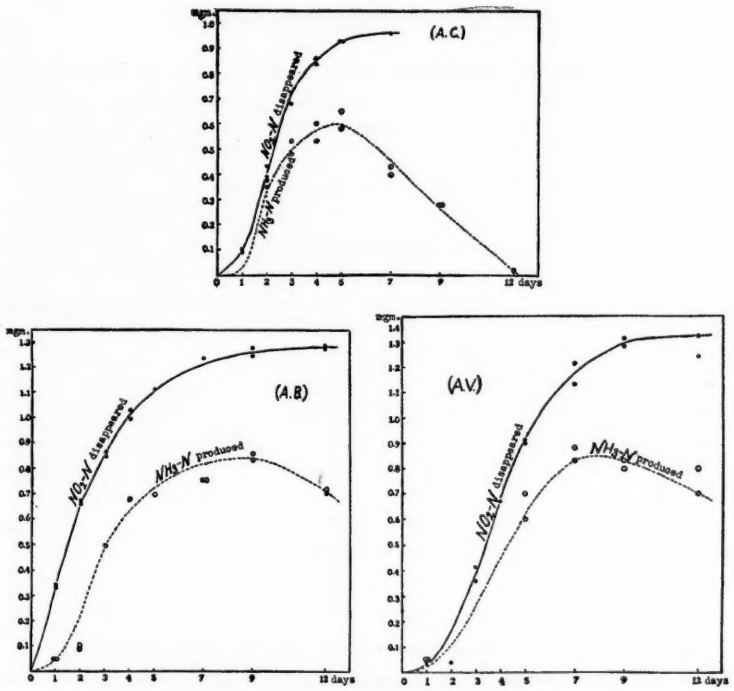

FIG. 2. PRODUCTION OF NH_3-N FROM NO_2-N BY AZOTOBACTER

A.C., A.B., and A.V. = *Azotobacter chroococcum*, *A. Beijerinckii*, and *A. vinelandii*, respectively. Culture solutions used: 20 cc. containing 8 mgm. KNO_2 (1.32 mgm. NO_2-N) with A.B. and A.V.; 15 cc. containing 5.81 mgm. KNO_2 (0.96 mgm. NO_2-N) with A.C.

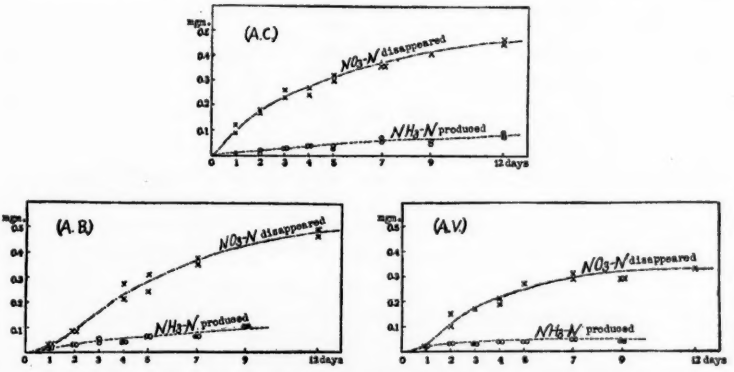

FIG. 3. PRODUCTION OF NH_3-N FROM NO_3-N BY AZOTOBACTER

A.C., A.B., and A.V. = *Azotobacter chroococcum*, *A. Beijerinckii*, and *A. vinelandii*, respectively. Culture solutions used: 15 cc. containing 4.3 mgm. KNO_3 (0.594 mgm. NO_3-N) with A.C.; 20 cc. containing 6 mgm. KNO_3 (0.832 mgm. NO_3-N) with A.B. and A.V.

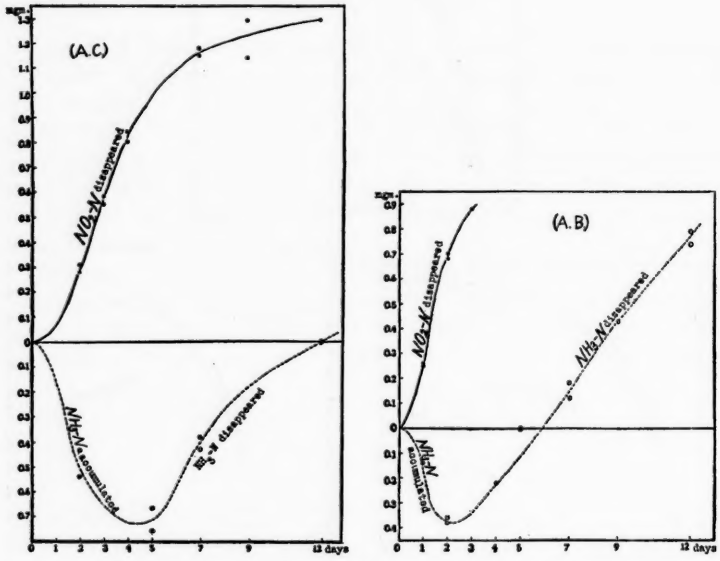

FIG. 4. SELECTIVE ABSORPTION OF NO_2-N AND NH_3-N BY AZOTOBACTER

A.C. and A.B. = *Azotobacter chroococcum and A. Beijerinckii*, respectively. Culture solutions used: 20 cc. containing 6.46 mgm. $NaNO_2$ and 6.18 mgm. $(NH_4)_2SO_4$ (1.3 mgm. NH_3-N and 1.3 mgm. NO_2-N) with A.C.; 20 cc. containing 4.32 mgm. $NaNO_2$ and 4.12 mgm. $(NH_4)_2SO_4$ (0.88 mgm. NH_3-N and 0.88 mgm. NO_2-N) with A.B.

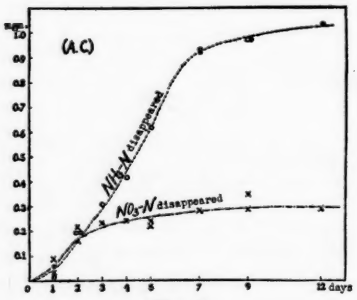

FIG. 5

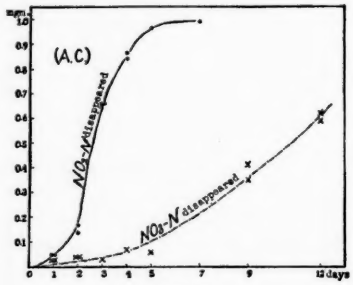

FIG. 6

FIG. 5. SELECTIVE ABSORPTION OF NH_3-N AND NO_3-N BY AZOTOBACTER CHROOCOCCUM

Culture solution used: 20 cc. containing 6 mgm. NH_4NO_3 (1.05 mgm. NH_3-N and 1.05 mgm. NO_3-N).

FIG. 6. SELECTIVE ABSORPTION OF NO_2-N AND NO_3-N BY AZOTOBACTER CHROOCOCCUM

Culture solution used: 20 cc. containing 6 mgm. KNO_2 and 6 mgm. KNO_3 (0.99 mgm. NO_2-N and 0.83 mgm. NO_3-N).

almost equal to the quantity of NH_3-N of $(NH_4)_2SO_4$ disappeared.[1] Furthermore, figure 6 shows that when equal quantities of KNO_2 and KNO_3 are added to culture solutions, the NO_2-N disappears much more rapidly than does the NO_3-N.

The production of hydroxylamine by Azotobacter. By obtaining oxime-N in culture solutions to which $NaNO_2$ and a small quantity of acetone were added, we have succeeded in demonstrating the production of hydroxylamine as an intermediate product in the reduction of nitrite to ammonia by Azotobacter. The experiment was carried out as follows: 200-cc. portions of Ashby's culture solution containing 0.005 per cent of $NaNO_2$ were put into 500-cc. Erlenmeyer flasks, sterilized in the usual manner, and inoculated with three strains of Azotobacter. To these solutions acetone was added (1,000 cc.: 1 cc.), and the flasks were kept at 30°C. From time to time, parts of the culture solutions were taken and tested for nitrite. After all the NO_2-N had disappeared, 2 gm. of $CaCO_3$ was added to each of the solutions, which was

TABLE 3

Absorption of nitrogen from $(NH_4)_2SO_4$ and NH_4NO_3 by Azotobacter chroococcum

TIME	$(NH_4)_2SO_4$	NH_4NO_3		
	NH_3-N disappeared	NH_3-N disappeared	NO_3-N disappeared	Total N disappeared
days	*mgm.*	*mgm.*	*mgm.*	*mgm.*
1	0.13	0.05	0.05	0.10
2	0.40	0.18	0.12	0.30
3	0.65	0.30	0.19	0.49
4	0.80	0.45	0.23	0.68
5	0.90	0.62	0.26	0.88

then distilled. The distillate was collected in a flask containing 10 cc. of 0.1 *N* HCl, boiled to decompose the oxime (quite possibly acetoxime), neutralized, and tested with the following reagents:

1. 0.5 gm. of sulfanilic acid was dissolved in 150 cc. dilute acetic acid.
2. 0.1 gm. of α-naphthylamine was dissolved in 20 cc. water, and the colorless liquid was mixed with 150 cc. dilute acetic acid.
3. 1.3 gm. iodine was dissolved in 100 cc. of glacial acetic acid.
4. 0.5 per cent of sodium thiosulfate solution.

To the neutralized liquid, 2 cc. of reagent 1 and three drops of reagent 3 were added and shaken from time to time. After 5 minutes, the excess of iodine was removed with reagent 4, and 1 cc. of reagent 2 was added and left for a few minutes. If hydroxylamine is present in the solution, a red color appears.

[1] The quantity of total N which disappeared in the case of NH_4NO_3 is a little smaller than that in the case of $(NH_4)_2SO_4$, probably because of the slower velocity of disappearance of NO_3-N compared to consumption of NH_3-N.

We have found that the three strains of Azotobacter used in this experiment produce hydroxylamine in culture solutions containing acetone, but the reaction was obtained only in traces when no acetone was present. We may conclude that hydroxylamine does not accumulate in culture solutions but is consumed (presumably via reduction to ammonia) immediately upon its production.

It is very interesting to observe that the toxic hydroxylamine is produced as an intermediate product in nitrite reduction by Azotobacter similarly to formaldehyde, which is believed by many to be produced as an intermediate product of the carbon assimilation by green plants.

SUMMARY

The decrease of NH_3-N, NO_2-N, and NO_3-N, added separately or in combination to solution cultures of three species of Azotobacter, has been determined. Ashby's solution was employed, without specific additions of iron or molybdenum, and no experiments are reported in which fixation of nitrogen occurred in such culture solutions containing fixed nitrogen.

The velocity of consumption of NO_2-N was the greatest; that of NO_3-N, the least.

In culture solutions containing nitrite, NO_2-N disappeared very rapidly, and NH_3-N accumulated, but this also disappeared rapidly after the complete disappearance of the nitrite.

When nitrate was added to culture solutions, a trace of nitrite and an accumulation of ammonia were found in the solution.

In culture solutions containing ammonium nitrite, the nitrite was for the most part first reduced to ammonia, even in the presence of added NH_3-N, and then absorbed by the bacteria.

From the aforementioned results, it is concluded that Azotobacter absorb nitrite, and possibly nitrate, mainly after reduction to ammonia.

Hydroxylamine is formed during reduction of nitrite to ammonia.

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CONTACT DEPLETION OF BARLEY ROOTS AS REVEALED BY RADIOACTIVE INDICATORS

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In a previous paper (2) we presented evidence for the existence of *contact effects* between plant roots and soil colloids. Whenever colloidal clay particles touch root surfaces, cations are transferred from the plant to the soil colloids. As a tentative theory we have assumed that such contact phenomena are the result of ion exchange between interpenetrating electric double layers, or more specifically, between overlapping oscillation spaces of adsorbed ions.

The recent discovery of artificial radioactivity provides a very sensitive and exceedingly simple method of chemical analysis. Moreover, the use of radioactive isotopes offers new perspectives for the study of ionic behavior in colloidal systems, in general, and in plants and soils, in particular. The present paper is an account of contact effect experiments conducted with radioactive sodium, potassium, and bromine. Again, the studies are concerned with contact depletion only; that is, transfer of nutrient ions from the root system to colloidal clay suspensions.

PRINCIPLES OF RADIOACTIVE INDICATORS

The cyclotron invented by O. E. Lawrence at the University of California is the most efficient tool for the creation of radioactive isotopes. The cyclotron produces high-speed protons and deuterons. Atomic nuclei, when subjected to bombardment by protons and deuterons undergo transformations which result in the production of radioactive isotopes. Physicists have been able to induce radioactivity in most of the elements of the periodic table. This achievement is opening new possibilities for research on many problems of biology and agriculture.

Transformation processes of atomic nuclei are expressed in the form of equations as shown in the following example:

$$_{11}Na^{23} + {}_{1}H^{2} \rightarrow {}_{11}Na^{24} + {}_{1}H^{1}$$

The equation indicates that ordinary sodium with atomic number 11 and

[1] The authors are indebted to D. R. Hoagland for valuable discussions and suggestions, and to E. O. Lawrence, director of the Radiation Laboratory, for supplying radioactive elements.

[2] Division of Plant Nutrition, College of Agriculture.

atomic weight 23 is bombarded by deuterons ($_1H^2$) of atomic number 1 and atomic weight 2. Deuterons are heavy hydrogen nuclei each of which consists of one proton ($_1H^1$) and one neutron ($_0n^1$). When deuterons strike Na with sufficiently high velocity the neutrons combine with Na and form an isotope ($_{11}Na^{24}$), that is, sodium with atomic number 11 but atomic weight 24. The protons ($_1H^1$) escape.

This artificially produced isotope of sodium is radioactive and disintegrates with a half-life period of 14.8 hours into magnesium ($_{12}Mg^{24}$), giving off beta radiations (β or $_{-1}e^0$) and gamma radiations (γ). The disintegration equation reads as follows:

$$_{11}Na^{24} \rightarrow {}_{12}Mg^{24} + {}_{-1}e^0 + \gamma$$

The corresponding equations for potassium and bromine are as follows:

$$_{19}K^{41} + {}_1H^2 \rightarrow {}_{19}K^{42} + {}_1H^1;\ {}_{19}K^{42} \rightarrow {}_{20}Ca^{42} + {}_{-1}e^0$$

$$_{35}Br^{81} + {}_0n^1 \rightarrow {}_{35}Br^{82};\ {}_{35}Br^{82} \rightarrow {}_{36}Kr^{82} + {}_{-1}e^0 + \gamma$$

From the standpoint of biological research one of the most significant characteristics of radioactive isotopes is their chemical behavior. Radioactive potassium, for instance, acts chemically like ordinary potassium. The two types of atoms cannot be separated by chemical means, since it is only the atomic nuclei which have different properties. The electron configurations, upon which the chemical behavior of the elements depends, are identical in both cases. Consequently, if a solution of KCl containing both ordinary and radioactive K—the latter in minute amounts—is used as a nutrient medium for plants, the roots should not be able to distinguish between the two kinds of ions and should accumulate both of them in their respective proportions. This, barley plants actually do, as will be shown elsewhere. Inasmuch as the radioactive members of the K ions continuously emanate β radiation, which may be easily detected with a Geiger counter, it is possible to trace the fate of the radioactive K within the plant in great detail. In this manner the radioactive isotopes serve as tags or indicators of ordinary elements.

METHODS OF EXPERIMENTATION WITH PLANTS

All tests were conducted with barley plants. These were grown according to the method of Hoagland and Broyer (1), as described previously (2). When the plants were about 3 weeks old, their roots were immersed in a solution containing radioactive elements. The migration of the radioactive isotopes into the shoots could be readily traced with the aid of the Geiger counter. By this means it was found that within 2 to 5 hours the plants accumulated substantial amounts of the radioactive elements.

The roots were then rinsed in flowing distilled water for about one minute, and subsequently were transferred to the test solutions. All experiments were

carried out with entire plants. The plants were grown from seedlings which had been fixed in the holes of supporting corks with nonabsorbent cotton. In most of the treatments reported here, the corks containing the plants were set in place in Mason jars to which had been added the desired solutions and suspensions. In all cases there were seven plants in one cork. In later discussions the expression, "one cork" will refer to the seven plants contained in one cork. The outgo of radioactive elements from the roots to the surrounding medium was ascertained by analysis of the nutrient solution for radioactivity.

Geiger counter

The activities of the samples were determined by the use of the Geiger-Müller or wire-and-cylinder type counting tube. The instrument was provided with a thin glass window to permit greater penetration of beta rays. The tube was filled with hydrogen gas at 10 cm. pressure. The cylinder was made of copper; and the central wire, of tungsten. As the behavior of the Geiger-Müller counter has been adequately described by Werner (3, 4), the following brief description of its action is sufficient: The tube is connected in series with a high resistance (5×10^6 ohms) and a high voltage (1200 volts). A beta ray or gamma ray on entering the tube initiates a corona discharge between the wire and cylinder by ionization of the H_2 gas. The corona current, i, in the high resistance, R, produces an iR potential drop which lowers the potential below the corona threshold, and the corona extinguishes. The iR drop of the instantaneous current can be amplified and counted by means of a suitable counting circuit. The instrument used in this research was provided with a Neher type amplifying circuit which operated a mechanical recorder. Since cosmic rays and other factors which are always present also cause discharges in the tube at a more or less constant rate, all counts of radioactive materials must be corrected for this so-called "background" count. Thus each count above the background corresponds to the disintegration of a single radioactive atom. The fraction counted of the total number of disintegrations of the sample depends, however, on the fraction of the total number of emitted beta or gamma rays which enter the tube.

Method of counting

The number of counts per minute obtained from a radioactive sample greatly depends on how close the substance is brought to the surface of the counter tube.

In the case of solutions which were strongly radioactive and emitted the penetrating gamma radiation (sodium and bromide), the counter tube, shielded by a pyrex centrifuging glass, was dipped directly into the liquid (400 cc.).

Radioactive K systems were measured in a different manner. An aliquot of 25 cc. was evaporated to dryness, and the residue was transferred to a watch glass and then held directly under the counter tube. Whenever salt solutions

had to be compared with clay suspensions, enough nonradioactive clay was added to the solution aliquots to guarantee strictly comparable conditions of counting.

All activities are expressed in "counts per minute." The variability of the atomic disintegrations calls for statistical treatment of the results. As a rule, we have made ten 1-minute readings with the counter and have calculated the mean error (M) of the mean according to the equation:

$$M = \sqrt{\frac{\sum d^2}{n(n-1)}},$$

where d denotes the difference of an observation from the arithmetical average and n indicates the number of observations.

At times the individual 1-minute readings were omitted, and only the sum total of the counts for a period of 5 to 10 minutes was recorded. Under such circumstances the mean error (M) was calculated from the equation:

$$M = \frac{\sqrt{c}}{m},$$

where c indicates the sum total of the counts obtained during the period of m minutes. As an illustration, the following data were obtained on 25 cc. of radioactive Mg-K-clay suspension. Counts per minute: 107, 81, 78, 106, 105, 83, 93, 102, 107, 105; average = 96.7 $\pm$3.83.

All errors reported in this paper refer to the error of counting as calculated from the foregoing equations. These values do not contain the variability of the corks (seven plants per cork) or the variations due to different treatments. The "over-all" error was determined in a special experiment involving 24 corks (seven plants each) and four widely different treatments consisting of six replications each. This error, calculated from the equation:

$$M_c = \sqrt{\frac{\sum d^2}{n-1}} \qquad (n = 24)$$

was 9.9 per cent, for one cork, whereas the counting error of this series amounted to only 1 to 3 per cent per cork. Depending on the accuracy of the counts, the errors listed in this paper exceed or fall below the over-all error. Consequently, if one wishes to test the significance of the difference of two types of treatments the mean error (or standard error) of one cork, which is 9.9 per cent, must be taken into consideration.

Background

In the present research the value of the background count varied between 15 and 30 counts per minute, depending on the locality (greenhouse or dark room inside a concrete building). The variability is indicated by the following typical series which comprises ten consecutive recordings of 1-minute duration

each. Counts: 19, 24, 22, 19, 16, 20, 31, 29, 27, 17; average = 22.4 ±1.51 counts per minute. The background was frequently measured.

All values for radioactivity were corrected for the background. The data obtained for Mg-K-clay may serve as an illustration.

Counts for Mg-K-clay	96.7 ±3.83
Background	25.3 ±1.69
Difference	71.4 ±4.18

The value of 71.4 ±4.18 counts per minute represents the radioactivity of 25 cc. of Mg-K-clay suspension, measured by the dry technic. The mean error of the difference (M_d) follows from the equation:

$$M_d = \sqrt{M_1^2 + M_2^2},$$

where M_1 and M_2 denote the mean errors of the two observations.

Correction for radioactive decay

When a radioactive substance is allowed to remain in the vicinity of a Geiger counter, it is found that the number of counts per minute decreases as a function of time. The decrease is governed by the relationship:

$$I = I_0 \, e^{-kt}$$

where I represents the intensity of radioactivity (e.g., counts per minute) at the time t and I_0, the initial intensity; k is a constant, characteristic of each radioactive element. In practice it is customary to express the rate of decay in terms of the half-life period; that is, the time interval during which the substance loses 50 per cent of its radioactivity. For potassium the value is 12.4 hours. The following equations hold for radioactive K:

$$\frac{I}{I_0} = \tfrac{1}{2} = e^{-k \cdot 12.4},$$

k becomes 0.0559, and

$$\frac{I}{I_0} = e^{-0.0559t}$$

Measurements obtained with the Geiger counter refer to I. To enable comparison of different observations, the counts must be expressed as I_0. All values for radioactivity reported in this paper refer to I_0. The mode of calculation is seen from the following example. Plants containing radioactive K were transferred to a Mg-clay suspension on July 5, at 4:52 p. m. After 3.80 hours (at 8:40 p. m.) 25 cc. of clay suspension was removed from the jar. Actual counting did not occur until 11:36 p. m. The counts, corrected for background, amounted then to 71.4 ±4.18 per minute, as shown in the pre-

ceding section. This value must be corrected for the time elapsed. The time $t = 0$ was arbitrarily selected for all measurements on July 5 as 4:00 p. m. The time interval is, therefore, 7.60 hours, and the equation assumes the form:

$$I_0 = \frac{I}{e^{-0.0559 \times 7.60}}, \quad \text{or} \quad I_0 = 1.53I$$

The value of counts, corrected for radioactive decay, is therefore 109 ±6.4. This represents the corrected radioactivity of 25 cc. of the Mg-K-clay suspension which had been in contact with plant roots for a period of 3.80 hours.

EXPERIMENTS WITH RADIOACTIVE POTASSIUM

All samples of radioactive potassium were prepared by bombarding metallic K with high-speed deuterons. To remove possible impurities (Na, Cu, Zn) the radioactive K was repeatedly recrystallized as potassium tartrate. The element was supplied to the plants in the form of potassium nitrate.

Behavior of radioactive K plants in distilled water

On June 3, 1938, the roots of seven plants which had accumulated radioactive K were immersed in 900 cc. of distilled water. This set was replicated three times. In a corresponding series 0.44 m.e. of $CaCl_2$ was added to provide a more suitable physiological solution. Tests for radioactivity of the water were run on 25-cc. aliquots after contact periods of 2.6, 10.8, and 55 hours. The average counts per minute above background are assembled in table 1. Some values are positive and some are negative, indicating that no significant outgo of K occurred. Moreover, the magnitudes are within the variability of the background, the mean error of which is ±1.62. The initial pH of water was 5.8; at the end of the experiment the pH was 4.8.

A second experiment was conducted on July 4. Aliquots of 25 cc. were drawn after immersion periods of 3.72 hours and 6.53 hours. The counts per minute above background were as follows:

$$H_2O \text{ (3.72-hour period)} = 8.1 \pm 3.82$$

$$H_2O \text{ (6.53-hour period)} = 6.6 \pm 5.36$$

Although both values are positive, their magnitudes are not highly significant. As the roots themselves gave 77,000 counts per minute, the loss of radioactive K, if any, must have been very small.

In summarizing, we may conclude that the barley plants under consideration possess a pronounced tendency to retain radioactive potassium against distilled water. These findings fully corroborate the results of our previous experiments in which excised barley roots did not lose measurable amounts of K to distilled water during 10 hours.

Behavior of radioactive K plants in electrolyte solutions

Plants containing radioactive K were placed in 900 cc. of various chloride solutions containing 5 m.e. of cation per liter and, in each case, 0.5 m.e. $CaCl_2$

per liter (June 3). After 11 hours the roots had rendered some of the solutions radioactive, as indicated in table 2. The counts for H_2O, LiCl, and NaCl were within the variability of the background and are therefore listed as "none." The values for $MgCl_2$, $CaCl_2$, $SrCl_2$, and $BaCl_2$ likewise did not exceed the background. A corresponding series with K salts (3 m.e. per liter) showed that the inorganic anions which are common to nutrient solution exerted no specific influence on the release of radioactive K from roots. As to the total amounts of K transferred, no accurate information can be given. The original KNO_3 solutions which contained radioactive K and into which the plants were placed for K absorption contained 0.000213 m.e. of total K per 100 counts per 25 cc. Since the ratio $\frac{\text{total K}}{\text{radioactive K}}$ is higher inside the plant than outside,

TABLE 1

Outgo of radioactive K into water

SYSTEM	COUNTS PER MINUTE PER 25 CC.		
	After 2.6 hours	After 10.8 hours	After 55 hours
Plants in distilled water	+0.6	−3.1	±0
Plants in H_2O + $CaCl_2$	+0.7	−0.3	+3.6

TABLE 2

Outgo of radioactive K from roots into electrolyte solutions

(Counts per minute, above background)

SOLUTION	FINAL pH	COUNTS PER MINUTE PER 25 CC.	SOLUTION	FINAL pH	COUNTS PER MINUTE PER 25 CC.
H_2O	5.80	None	KCl	4.50	42.8 ±9.8
LiCl	5.75	None	KNO_3	6.05	47.2 ±9.5
NaCl	5.20	None	K_2SO_4	3.85	40.4 ±9.8
KCl	4.40	62.5 ±10.5	KH_2PO_4	4.10	47.1 ±10.8
HCl	2.45	219 ±11.8	$KHCO_3$	6.70	35.7 ±10.7

we may only infer that *at least* 0.000213 m.e. of K per 100 counts per 25 cc. must have left the roots.

In conclusion it may be said that the barley roots have a tendency to yield measurable amounts of K to certain electrolyte solutions. No such losses were observed in our previous experiments. Probably the great sensitivity of the radioactive method accounts for the discrepancy. It is probable, however, that the losses in the case of the rather strong HCl (0.005 *N*) solution are due to injury.

Behavior of radioactive K plants in clay suspensions

The clays used in the present study are bentonites and Yolo clay colloids. Both consist of the common clay mineral montmorillonite. The base-saturated

bentonites were prepared by adding hydroxides to electrodialyzed colloids. Their base-exchange capacity as determined with neutral ammonium acetate is 100 m.e. per 100 gm. oven-dry material. The base-saturated Yolo colloids were obtained by extensive leaching with neutral salts. The base-exchange capacity of these clays is 55 m.e. per 100 gm.

Corks holding seven radioactive plants were transferred, on June 3, 1938, to clay suspensions and salt solutions of 900 cc. volume each. All jars contained 4.5 m.e. of total cations and, in addition, 0.45 m.e. $CaCl_2$. After a contact period of 53 hours the counts listed in table 3 were obtained from the solutions and suspensions. In all cases the K- and Na-clay sols give higher counts than do the corresponding K and Na chlorides. In other words, the plant

TABLE 3

Outgo of radioactive K from roots into clay suspensions and chloride solutions (53 hours)

SOLUTIONS	COUNTS PER MINUTE PER 25 CC.	CLAY SOLS	COUNTS PER MINUTE PER 25 CC.
H_2O	None	H_2O	None
NaCl	None	Na-Yolo clay	606 ±93
KCl	314 ±69	K-Yolo clay	374 ±60

TABLE 4

Outgo of radioactive K from roots into chloride solutions and clay suspensions containing divalent cations

SALT SOLUTIONS			CLAY SUSPENSIONS (1 PER CENT)		
Type	Initial pH	Counts per minute per 25 cc.	Type	Initial pH	Counts per minute per 25 cc.
$MgCl_2$	6.35	3.3 ±4.1	Mg-Yolo	7.20	109 ±6.4
$CaCl_2$	6.00	11.3 ±3.7	Ca-Yolo	7.25	66.3 ±3.8
$CaCO_3$	9.45	17.0 ±4.1			
$SrCl_2$	6.10	13.5 ±4.6	Sr-Yolo	6.75	68.4 ±6.3
$BaCl_2$	6.10	2.8 ±3.5	Ba-Yolo	6.85	45.2 ±4.8

roots lost more K to the clay suspensions than to the true solutions. This feature is particularly pronounced for the Na-systems. For the K-systems the difference does not exceed the limits of variability.

Further confirmation was obtained on July 4, when the roots were kept for 3.7 hours in 400-cc. Mason jars. Table 4 shows the results obtained with divalent cations for concentrations amounting to 5.5 m.e. per liter. The data convincingly prove the great superiority of the clay sols in extracting radioactive K from barley plants. The value for Mg-Yolo clay is highest among the di-clays.

At the same time a strict comparison was made between monovalent and divalent cations. This was carried out in the form of a concentration series which comprised the systems KCl, $CaCl_2$, K-Yolo clay, and Ca-Yolo clay.

The amounts of cations contained in 400 cc. were 0.67, 2.2, 11.0, and 22.0 m.e. The counts per minute per 25 cc. are graphically illustrated in figure 1. Two features are outstanding: first, the systems with monovalent cations, whether chlorides or clay sols, caused the loss of more radioactive elements from the roots than did the media containing divalent cations; second, the clay systems, irrespective of the valence of the adsorbed cations, gained more radioactivity than the true solutions.

In general, the observations with radioactive K fully confirm our previous results on the influence of colloidal particles on the ion distribution between plant roots and clay media. New is the observation that divalent cations, if

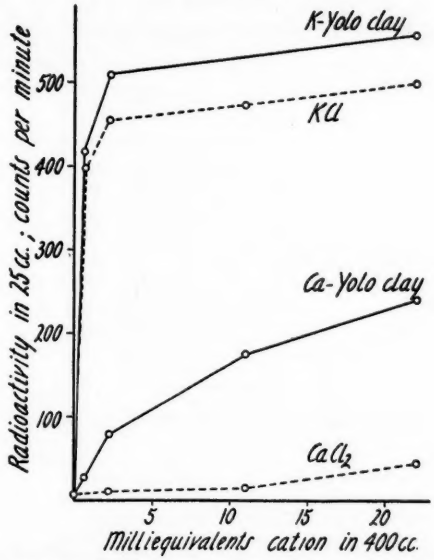

FIG. 1. OUTGO OF RADIOACTIVE POTASSIUM FROM ROOTS INTO CLAY SUSPENSIONS AND SALT SOLUTIONS

adsorbed on clays, also reduce the K level of the barley plants used in these investigations.

EXPERIMENTS WITH RADIOACTIVE SODIUM

Metallic sodium, after treatment with high-speed deuterons, was dissolved in water, filtered to remove insoluble hydroxides and carbonates, and neutralized with HCl. On June 1, 1938, radioactive Na as NaCl (1.9 m.e. total Na) was added to the Hoagland solutions in the pans used for growing plants. The shoots became strongly radioactive, after an absorption period of 3 hours. After the roots had been rinsed with distilled water, the plants were transferred to pint Mason jars containing the desired salt solutions and clay suspensions.

The media were tested for radioactivity after 3 hours and 16 hours. The counts per minute are presented in table 5. The outstanding difference between the radioactive Na and K plants is the significant loss of radioactive Na to distilled water. Whether this is characteristic for Na in general or merely a consequence of the Na status of the barley plants investigated is not known. In contrasting clays with solutions, it is seen that the sols tend to enhance the outgo of Na from the roots, especially after prolonged periods of contact. Strict comparison is not possible since the systems differ in their cation composition. This objection does not apply to the data in table 6 which shows the

TABLE 5

Outgo of radioactive Na from roots into true and colloidal solutions

SYSTEM	COUNTS PER MINUTE	
	After 3 hours	After 16 hours
H_2O	106 ±4.4	194 ±10
KCl (5 m.e./l.)	108 ±7.5	316 ±17
$CaCl_2$ (5 m.e./l.)	106 ±7.3	52 ±8.6
Hoagland solution	101 ±7.1	247 ±15
H-Putnam clay	83 ±6.8	375 ±18
H-Cecil clay (0.5 per cent)	96 ±7.1	357 ±18
H-Lindley clay	185 ±9.3	498 ±20
H-peat (2.2 per cent)	309 ±12	603 ±22
H-bentonite (0.5 per cent)	280 ±11	668 ±27

TABLE 6

Outgo of radioactive Na from roots into Na-systems

SYSTEM (5 M.E. Na PER LITER)	COUNTS PER MINUTE	
	After 3 hours	After 16 hours
H_2O	106 ±4.4	194 ±10
NaCl	102 ±7.2	229 ±14
$NaHCO_3$	78 ±6.5	298 ±16
Na-bentonite	147 ±8.4	339 ±17

loss of radioactive Na to various Na solutions and Na-clay suspensions. Again the colloidal solutions acquire the highest amounts of radioactivity.

Briefly summarized, the findings with radioactive Na corroborate the observations made with K as far as the efficiency of root depletion by colloidal systems is concerned.

EXPERIMENTS WITH RADIOACTIVE BROMINE

For most clays the adsorption capacity for anions such as Cl, Br, NO_3, and SO_4 is very low. One would not anticipate therefore an enhanced withdrawal of Br from barley roots by clay particles.

If a flask containing ethyl bromide is placed in the path of neutron rays, radioactive Br_2 is formed. NaBr is obtained by shaking the ethyl bromide with a mixture of Na-sulfite and Na-bicarbonate solutions. Purification of the extract was carried out by steam distillation (140° C.), after addition of phosphoric acid. The resulting HBr was neutralized with KOH. Radioactive KBr thus produced was added to pans of solution to the extent of 0.35 m.e. of total Br per 168 plants (Sept. 22, 1938). After 5 hours the plants, seven per cork, were transferred to the salt and clay solutions where they remained from 4 to 9 hours. The radioactivity was tested on the total 400-cc. sample.

From the data in table 7 some very interesting conclusions may be drawn. As was anticipated, the clay colloids no longer exceed the chlorides in their ability to extract nutrient ions from plants. In all cases, the counts for the suspensions of negative particles are below those for the solutions. On the

TABLE 7

Outgo of radioactive Br from barley roots into salt solutions and clay sols

PURE SOLUTIONS	INITIAL pH	TIME	COUNTS PER MINUTE	COLLOIDAL SOLUTIONS	INITIAL pH	TIME	COUNTS PER MINUTE
		hours				*hours*	
H_2O	5.80	5.6	15.6 ±2.1	Na-Yolo clay	7.50	8.5	19.6 ±2.3
NaCl	5.80	8.6	27.5 ±2.5	K-Yolo clay	7.00	6.3	17.4 ±2.1
KCl	6.05	6.4	29.9 ±2.4	Mg-Yolo clay	7.05	7.7	5.5 ±1.9
$MgCl_2$	5.85	8.3	10.0 ±3.7	Ca-Yolo clay	7.15	6.4	6.9 ±1.9
$CaCl_2$	6.15	7.7	88.6 ±3.5	H-Yolo clay	4.65	5.7	11.1 ±1.9
$KHCO_3$	9.55	6.5	110.0 ±3.8	Aiken soil	6.50	5.3	11.0 ±1.9
$KHCO_3$	6.95*	17.8	24.3 ±2.9	$Fe(OH)_3$	.....	5.5	37.2 ±2.5

* Final pH.

other hand, the electrodialyzed iron hydroxide sol which contains no free electrolytes exceeds the water value by more than 100 per cent. These observations are in harmony with colloid chemical considerations, since the negative clay particles have no affinity for halogen anions whereas the positive iron hydroxide particles will adsorb bromides. Such findings forcefully bring to the fore the importance of soil colloids in influencing the ion status of root systems.

MEMBRANE EXPERIMENTS

Contact depletion of living roots by clay particles should not take place if the two colloidal systems are separated by a membrane which permits passage of small ions only. On November 4, at 9:00 p. m. radioactive K plants were placed in four pyrex trays containing 1200 cc. of distilled water which was aerated continuously. Into each vessel was dipped a pyrex flash which had a bottom consisting of a semipermeable membrane (Visking casing). At the

beginning of the experiment the following solutions, 50-cc. each, were introduced into the membrane flasks:

Flask 1: H_2O.
Flask 2: KCl (6.25 m.e.).
Flask 3: $KHCO_3$ (6.25 m.e.).
Flask 4: K-Yolo clay (6.25 m.e.).

After 12.3 hours, during which time the solutions and suspensions inside the membrane flask were constantly agitated with a stream of carbon dioxide, counts were taken of the entire 50 cc. of the solutions inside the membrane (the roots were outside the membrane). The counts above background were as follows:

H_2O	0.6 ± 1.97
KCl	16.1 ± 1.36
$KHCO_3$	49.1 ± 2.54
K-Yolo clay	6.8 ± 1.77

The result shows that in the presence of the membrane the clay solution was less effective than were the salt solutions, whereas in the absence of a membrane the contrary effect was observed, as indicated by all our previous experiments. In a parallel experiment run under identical conditions, but without a membrane, the following counts for 50-cc. solutions were obtained:

H_2O	2.5 ± 4.3
KCl	60.8 ± 5.9
$KHCO_3$	58.8 ± 6.1
K-Yolo clay	76.4 ± 5.8

In harmony with our previously reported data on excised roots in which it was shown that membranes prevent the withdrawal of K from excised barley roots by H-bentonite, it must be concluded that contact is a necessary requirement for the observed cation removal from roots by colloidal clay particles.

A NEW ASPECT OF IONIC INTERRELATION OF PLANT ROOTS AND NUTRIENT MEDIA

The use of radioactive isotopes has brought to light a process which no other technic could have revealed. As seen from figure 1 the KCl solutions and the K-clay suspensions show marked gains of radioactive potassium which has been given off by the roots. Now, we have good evidence to assert that the very same plants have accumulated substantial amounts of K from the media. One must conclude, therefore, that potassium migrated simultaneously in opposite directions, namely, into the root and out of the root. These relationships were examined quantitatively on June 3, 1938. Twelve corks each holding seven plants containing radioactive K were placed in a shallow tray of pyrex glass which contained 1800 cc. of K-Ca-bentonite suspension (0.35 per cent). The suspension, which was renewed five times at intervals of 1

hour, acquired a total activity corresponding to 53,640 counts per minute. As the radioactivity of the original KNO_3 solution was 1 count per 2.13×10^{-6} m.e. K, the 84 plants must have given off 0.114 m.e. K to the K-Ca-bentonite suspensions. This value represents a minimum amount only, for reasons already given. Prior to immersion in K-Ca-bentonite, the roots weighed 4.51 gm. (on an oven-dry basis) and contained 1.685 m.e. K; afterwards, the analysis showed 2.840 m.e., or a gain of 68.3 per cent. Actually the roots must have absorbed a larger amount of K, since at least 0.114 m.e. moved out of the plants. The accumulation of 1.155 m.e. K represents a net intake which may be considered as the consequence of ion interchange between radioactive and ordinary K of the plant and ordinary K of the solution.

Similar relationships exist for other cations. According to table 5, radioactive Na roots lose Na to Na-bentonite while at the same time they more than double their original Na level. Radioactive Br roots (table 7) transplanted in KBr give off 30.1 $\pm$1.98 counts per minute within 4.3 hours; yet they absorb large amounts of the electrolyte.

In view of the findings, our concepts of the mechanism of electrolyte absorption by plants must be modified and extended. The results show that the intake of ions is not a uni-directional process; ions of the same species may move into the root and out of the root at the same time. *The outgo is especially pronounced when the roots are in contact with colloidal systems.*

The outgo of ions through contact effects can occur with actively metabolizing root systems, capable of further salt absorption, but it is not yet possible to state the role of metabolism in the loss of mineral ions to colloids or to salt solutions, although certain experiments suggest that root metabolism associated with salt accumulation may have a relation to the exchange processes which bring about loss of ions from the root system. This question is under further investigation. At present, emphasis is placed on the general phenomenon of removal of ions from active roots, especially under conditions of root-colloid contacts. This, in itself, has an interesting and important bearing on certain problems of soil-plant interrelations, regardless of the nature of the physiological or chemical mechanisms of the root resulting in loss of ions.

THE PROBLEM OF ROOT INJURY

The foregoing experiments convincingly demonstrate the significance of ion interchange between roots and colloidal clay particles. Moreover, the trials with membranes strongly point toward the existence of a specific contact phenomenon which we interpret as an ion interchange between intermingling electric double layers. For obvious reasons, such a picture is purely theoretical, since all knowledge of the fine structure of root surfaces and the behavior of ions on surfaces in general is based on inferences. Indeed, one might contend that the entire effect is merely the result of injury of roots. One might suggest that in healthy roots the movement of an ion in process of accumulation is

uni-directional and that any loss of an ion of the same species constitutes definite proof of cell injury.

For the systems under consideration two main sources of root injury should be taken into consideration. One of them may be an unfavorable balance of electrolytes in the culture solution; the other, a direct effect of the colloidal particles such as physical rupture of cell walls or localized dehydration.

Regarding the pure electrolyte effect we note from preceding tables that the roots lose radioactive K to mixtures of salts containing Ca ions as well as to single salt solutions comprising monovalents cations. According to table 5, roots, within 3 hours, transfer radioactive sodium in equal amounts to H_2O, KCl, and Hoagland solution. In a special experiment in which roots of plants containing radioactive K were placed in flowing nutrient solution (full Hoagland solution), 23.7 per cent of the total radioactivity of the roots was removed in 48 hours.

Unless one maintains that nutrient solutions of the Hoagland type are toxic or injurious to roots, there is little justification for attributing the outgo of cations from roots to electrolyte injury. The other alternative, namely, the belief that the observed simultaneous transfer of ions from root to media, and vice versa, is a normal process of healthy roots, appears preferable.

In regard to direct contact injury the H- and K-colloids should be most harmful, since they deplete the roots more efficiently than other types of clay. One would expect that such disturbances of roots cells are accompanied by losses of *anions* as well as cations, a criterion which may be easily subjected to experimental verification. The results obtained with radioactive bromide anions (table 7) constitute sufficient proof that colloidal clays in general and H-clay in particular do not cause significant losses of Br. The counts for H-Yolo clay are even below those of distilled water. Thus if a plant contains sufficient amounts of KBr, a H-clay will pull out K but not Br, whereas a positive iron hydroxide sol removes Br, but not K, from the roots. Such behavior of roots does not speak in favor of the direct injury hypothesis.

The following test for injury is particularly illuminating:

Radioactive barley roots possessing an activity of 7330 counts per minute were placed into 400 cc. of distilled water, H-Yolo clay, and K-Yolo clay suspensions. After a contact period of 2.58 hours the solutions had acquired the following activities (counts per minute per 25 cc.):

H_2O	6.1	±2.6
H-clay	132	±4.4
K-clay	193	±7.1

All plant roots were then washed for 1 minute and immediately transferred to distilled water for the purpose of learning whether or not the roots continued to give off large amounts of radioactive K. This should occur if the aforementioned losses of K were the result of root injury. Although the measurements were taken for short intervals, all systems gave very low counts (table 8),

for the technic employed in this study. Especially conclusive are the results of the K-clay systems in which the roots released 42 per cent of their radioactivity to the clay suspensions but, after transfer to distilled water, immediately reduced the outgo of K to such a low degree that no losses could be detected with the present method of counting. Any injury resulting from contact with clay particles must have been concomitant with the period of treatment, and it must have ceased at once thereafter. It is doubtful that "injury" is the appropriate term to describe such plant behavior.

GENERAL CONCLUSIONS

The investigations with radioactive isotopes fully confirm the contact depletion effects observed in previous studies with excised barley roots.

It is now fairly certain that the classical theories of soil solutions no longer suffice to explain fully the absorption of mineral elements by plants from soils. They must be supplemented by considerations of contact effects. Although contact intake has not yet been proved, the converse phenomenon, namely, contact depletion, is well established for the barley plants herein described.

TABLE 8

Injury test

SYSTEM	COUNTS PER MINUTE PER 25 CC.		
	After 15 minutes	After 1 hour	After 2.58 hours (extrapolation)
Water-roots into H_2O	2.3 ±6.5	5.7 ±6.7	12.5 ±19.4
H-clay-roots into H_2O	13.4 ±7.1	21.6 ±7.6	43.8 ±17.1
K-clay-roots into H_2O	10.5 ±7.0	8.0 ±7.1	3.1 ±2.3

No general conclusions regarding the practical significance of the results should be drawn before more soils and different plants at various growth stages have been examined.

SUMMARY

The principles of radioactive indicators and their adaptation to the study of contact interchange of cations between plant roots and soil colloids are described.

Barley plants containing radioactive potassium retain this isotope against distilled water but release it to salt solutions and clay suspensions. For equal amounts of cations in the nutrient media, the colloids greatly exceed the single-salt solutions in removing radioactive K from plant roots. The outgo of radioactive K from plants increases with concentration of the nutrient media and time of contact.

Experiments with barley plants containing radioactive sodium also show that colloidal clay suspensions are more efficient depleting agents than are salt solutions of corresponding cation concentrations.

These relationships are reversed if direct contact is prevented by placing semipermeable membranes between the roots and the clay particles.

For plants containing radioactive Br anions the clay suspensions remove smaller amounts of the isotope from the roots than do the corresponding salt solutions.

Various experiments are reported which indicate that contact depletion of roots by clay particles is not the result of root injury.

It is shown that the intake of ions by roots is not a uni-directional process; ions of the same species may move into the root and out of the root at the same time.

The results obtained with radioactive elements fully confirm the previously published data obtained with total K analyses of excised barley roots. It is now fairly certain that the theories of chemical soil solution no longer suffice to explain fully the absorption of mineral elements by plants from soils. They must be supplemented by considerations of contact effects.

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THE NATURE OF LATERIZATION AS REVEALED BY CHEMICAL, PHYSICAL, AND MINERALOGICAL STUDIES OF A LATERITIC SOIL PROFILE FROM PUERTO RICO[1]

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The exact nature of the laterization process is not definitely known. It is accepted, however, that laterization is a weathering process which takes place in the humid tropics and subtropics and which is characterized by the removal of bases and silica from, and the accumulation of the hydroxides and sesquioxides of aluminum and iron in, the surface horizon (10; 11; 14, p. 366–418; 16; 19; 34, p. 274–337). It has also been pointed out that lateritic soils may be podzolized (34, p. 274–337); that the process of primary laterization may be succeeded by one of resilication (12); that the upward capillary movement of iron in the soil profile (10, 11), and subsoil exposure due to erosion (22, 24), may be factors influencing laterization. That laterization is, perhaps, more strictly a geologic than a pedologic process has likewise been mentioned (15).

Physical and mineralogical studies of lateritic soils have been reported by Bennet and Allison (1, p. 83–84), Fettke and Hubbard (4), Fox (5), Leith and Mead (17, p. 25–44), Mattson and Gustafsson (21), Roberts (26), and Shibuya (32); and chemical studies by various methods have been reported by Harada (8), Hardy (9), and Harrison (12).

Lateritic soils are discussed further by Bonnet (2, 3), Fox (5), Glinka (7), Harrassowitz (10, 11), Imperial Bureau of Soil Science (13), Joffe (14, p. 366–418), Kellogg (15), Marbut (19, 20), Mohr (22), Principi (25), Robinson (27, p. 325–329), Russell (30), and Thorp (34, p. 274–337).

SOIL USED FOR INVESTIGATION

In order to gain further information relative to the laterization process, chemical, physical, and mineralogical studies were made of Catalina clay, the most extensive lateritic soil type of Puerto Rico. This soil, of the mountain and hill lands, which usually occurs where the rainfall is more than 79 inches,

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is derived from andesitic tuff. The depth to rock, ranging from 3 to 40 feet, usually increases with increasing annual rainfall and with the gentleness of the slopes. The surface ranges from rolling to steep, but most of the hills are rounded and are cut by gently sloping ravines. The soil is well drained but is affected by sheet erosion. Like other lateritic soils, Catalina clay exhibits no sharp distinctions between horizons. The surface layer is light red to reddish brown friable clay, the depth of which varies with surface relief from about 4 to 8 inches. The subsurface layer is reddish brown or light red, slightly heavy, friable clay extending to a depth of about 24 inches. Below this is red clay, which continues to great depths. Catalina clay is everywhere acid. It is a poor nitrifying soil, as shown by Bonnet (3) elsewhere. One of the best soils for the growing of coffee, it produces profitable yields of various other crops such as sugar cane, citrus, and pineapple, when properly fertilized.

Six soil samples were taken, May 27, 1937, on Catalina farm, which is at Km. 5.1 of the new Mameyes-Yunque road. The samples were labelled as follows:

A_1 (0–12 inches)—reddish brown friable clay
A_2 (12–36 inches)—brownish red friable clay
B_1 (36–84 inches)—red clay, heavier than A_2 and plastic
B_2 (84–120 inches)—red clay heavier than B_1
C_1 (120 inches)—friable rotten parent material
C_2 (240 inches)—same as C_1

The first two samples were taken with a soil auger in various places of the nearby field; other samples were taken from a fresh cut in the road. The samples were air-dried, sifted through a 20-mesh sieve, and stored in screw-capped jars.

TOTAL SILICA, SESQUIOXIDES, AND BASES IN CATALINA CLAY

Observations were made on the distribution of total silica, sesquioxides, and bases in the profile of Catalina clay. Table 1 contains data for two horizons of the solum and two of the parent material. The results show that the highest contents of total silica and alumina are in the C_1 horizon and the highest content of iron is in the C_2. Results do not point to the leaching of silica from the solum, but they tend to show some accumulation of iron oxide in the A_1 horizon. The parent material is more acid than the solum. The surface soil is well supplied with organic matter.

FREE SILICA AND SESQUIOXIDES IN CATALINA CLAY

As lateritic soils require a more drastic treatment than that of other soils for the removal of free silica and sesquioxides, the following modification, recommended by Truog et al. (35), was used: Five-gram samples, pretreated with 10 per cent hydrogen peroxide to remove organic matter, were given five consecutive treatments with boiling sodium sulfide-oxalic solution for removal of the free iron and aluminum oxides and the free colloidal silica. The extract

was clarified by centrifuging and was saved for determinations of silica, iron, aluminum, and titanium. The residue was extracted further by two consecutive 30-minute treatments with boiling 2 per cent sodium carbonate. The extracts were centrifuged and saved separately for determinations of silica, iron, aluminum, and titanium. The results of these determinations were added to those from previous extracts.

The free iron oxide rises from 13 per cent in the B_2 horizon to 15 per cent in the A_1, and the free alumina rises from 5 to 9 per cent (table 2). This shows a

TABLE 1

Chemical analysis of Catalina clay

Oven-dry basis

HORIZON	DEPTH	pH	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	MnO	TiO_2	LOSS ON IGNITION	ORGANIC MATTER*
	inches		*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
A_1	0–12	5.3	33.70	19.07	31.00	0.18	0.03	0.04	0.33	17.22	6.17
B_1†	36–84	5.5	35.40	15.60	30.73	0.51	0.30	0.04	0.86	13.75	0.68
C_1†	120+	4.3	38.56	13.86	31.48	0.34	0.67	0.01	0.65	14.22	0.66
C_2†	240	4.4	32.70	21.10	26.20	0.10	1.05	0.14	0.19	12.80	0.22

* Determined by Schollenberger's method (31).

† Analyzed by C. J. Rehling, I. C. Gregory, and H. D. Merwin, respectively, soils department, University of Wisconsin.

TABLE 2

Free silica, sesquioxides, and titanic oxide in Catalina clay

Oven-dry basis

HORIZON	DEPTH	SiO_2	Fe_2O_3	Al_2O_3	TiO_2
	inches	*per cent*	*per cent*	*per cent*	*per cent*
A_1	0–12	2.03	15.04	8.87	0.01
A_2	12–36	3.83	14.94	8.33	0.08
B_1	36–84	4.05	13.35	6.97	0.04
B_2	84–120	2.16	13.06	5.21	0.08
C_1	120+	9.00	11.76	9.20	0.03
C_2	240	2.85	17.79	4.34	0.10

tendency for the free sesquioxides to accumulate in the upper solum. Results do not point to the leaching of free silica from the solum. The highest contents of free silica and alumina are in the C_1 horizon, and the highest content of iron is in the C_2.

DISTRIBUTION OF THE MECHANICAL SEPARATES IN CATALINA CLAY

Mechanical analyses of lateritic soils are more accurate after the removal of colloidal binding substances which interfere with the dispersion of the fine particles. Organic matter, free iron oxide (hydrated and unhydrated), and

inorganic base-exchange material are involved in this connection. Colloidal silica and free alumina may also be involved. Truog et al. (35) recommend a special type of mechanical procedure after the removal of these binding agents.

The soil fractions were separated by means of a No. 2 International centrifuge, in accordance with the size limits of the Atterberg system: sand (2,000—20 μ), silt (20—2 μ), clay (< 2 μ). The clay was further subdivided at the 0.2 μ size into coarse and fine clay (36).

TABLE 3

Mechanical analysis of Catalina clay

Oven-dry basis

HORIZON	SAND (>20μ)	SILT (2–20μ)	COARSE CLAY (0.2–2μ)	FINE CLAY* (<0.2μ)	FINE CLAY†	TOTAL CLAY (<2μ)	ORGANIC MATTER AND MATERIAL LOST IN PROCESS
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
A_1	1.79	3.77	21.42	63.08	37.14	84.50	9.94
A_2	1.64	2.71	37.12	50.34	23.16	87.46	8.19
B_1	2.83	8.34	50.68	30.18	5.09	80.86	7.97
B_2	3.51	12.90	57.12	24.40	3.96	81.52	2.07
C_1	2.07	18.73	32.58	43.41	13.39	75.99	3.21
C_2	8.34	13.15	36.91	33.03	7.95	69.94	8.57

* Includes free silica and sesquioxides.

† Does not include free silica and sesquioxides.

TABLE 4

Exchange capacity of the silt and coarse and fine clay fractions of Catalina clay

m.e. per 100 gm. material

HORIZON	SILT	COARSE CLAY	FINE CLAY	SOIL
	m.e.	*m.e.*	*m.e.*	*m.e.*
A_1	4.4	6.9	9.9	8.4
A_2	6.0	7.1	5.5	8.1
B_1	6.3	8.7	6.2	8.6
B_2	9.3	11.2	2.3	6.3
C_1	8.9	9.8	7.9	9.9
C_2	9.4	11.8	10.2	6.6

Table 3 shows the distribution of the mechanical separates in the various horizons of Catalina clay. The clay content of the soil profile is very high, varying between 70 per cent in the C_2 horizon and 87 per cent in the A_2. The silt fraction decreases going upward from the C_1 to the A horizon. Fine clay decreases markedly and coarse clay increases markedly going upward from the C to the B horizon; above that, the coarse clay decreases and the fine clay increases regularly from the B to the A horizon.

EXCHANGEABLE BASES AND AVAILABLE NUTRIENTS IN CATALINA CLAY

The extent to which the weathering process has affected the exchangeable bases in the Catalina clay profile is shown in tables 4 and 5.

The exchange capacity of the soil profile is rather low, varying between approximately 6 m.e. in the B_2 horizon and 10 m.e. in the C_1. The exchange capacity of the silt and coarse clay fractions increases, and that of the fine clay decreases with solum depth (table 4).

Bases, especially lime, are distributed more or less uniformly in the first three horizons; about three-fourths of the exchange material is saturated equally with calcium and hydrogen. The exchangeable hydrogen is higher in the C_1 horizon than in the C_2 (table 5). There is a sharp pH change between the andesitic tuff and the soil parent material; the pH of the former is 8.2 and that of the latter is 4.4.

TABLE 5

Exchangeable bases and hydrogen, total exchange capacity, and pH of Catalina clay

m.e. per 100 gm. dry soil

HORIZON	DEPTH	K	Ca	Mg	H	TOTAL EXCHANGE CAPACITY	pH
	inches	*m.e.*	*m.e.*	*m.e.*	*m.e.*	*m.e.*	
A_1	0–12	0.19	3.40	1.52	3.29	8.40	5.3
A_2*	12–36	0.13	3.33	1.01	3.63	8.10	6.4
B_1*	36–84	0.09	2.80	1.72	3.99	8.60	5.5
B_2	84–120	....	....	....	....	....	4.4
C_1*	120+	0.19	0.64	1.22	7.85	9.90	4.2
C_2*	240	0.07	0.75	0.91	4.87	6.60	4.4
D	Andesitic tuff	....	....	....	....	....	8.2

* Analyzed by D. M. Batson, C. J. Rehling, I. C. Gregory, and H. D. Merwin, respectively, soils department, University of Wisconsin.

SPECIFIC GRAVITY SEPARATION OF THE MINERALS IN CATALINA CLAY

The minerals of the silt and coarse clay fractions were separated into specific gravity groups as recommended by Pearson and Truog (23). Mixtures of symmetrical tetrabromoethane (sp. gr. 2.98) and nitrobenzene (sp. gr. 1.20) were used for the separation of minerals.

The specific gravity separations were made in accordance with the following scheme:

SPECIFIC GRAVITY GROUP	MINERAL GROUPS
>2.98	Iron minerals, muscovite, biotite, zircon, rutile
2.70–2.98	Talc, plagioclase
2.50–2.70	Quartz, plagioclase and potash, feldspars, chlorite
<2.50	Clay minerals

The results, in table 6, show that the bulk of the silt fraction is comprised of minerals the specific gravities of which are less than 2.7. The heavier

minerals are evenly distributed between the specific gravity groups 2.70–2.98 and >2.98. In the A_1, A_2, and B_1 horizons the lighter minerals are evenly distributed between the specific gravity groups 2.5–2.7 and <2.5. In the B_2 and C_2 horizons, however, the largest percentage of the minerals is in the specific gravity group 2.5–2.7; and in the C_1 horizon, in the specific gravity group <2.5.

IDENTIFICATION OF THE MINERALS IN CATALINA CLAY

The minerals were identified qualitatively by petrographic methods. Observations made on a thin section of the consolidated parent rock of Catalina clay revealed the following minerals: abundant augite and serpentine, appreciable quantities of calcite and chlorite, and little andesine and glass. Observations were also made of the sand and specific gravity groups of the silt and coarse clay from the various horizons in the Catalina clay profile, according to the following scheme:

TABLE 6

Specific gravity separates of the silt (2–20μ) fraction of Catalina clay

HORIZON	SP. GR. >2.98	SP. GR. 2.70–2.98	SP. GR. 2.50–2.70	SP. GR. <2.50	LOST IN MAKING SEPARATIONS
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
A_1	3.5	4.3	42.8	39.2	10.2
A_2	5.8	2.8	45.4	42.0	4.0
B_1	5.2	2.4	42.0	42.4	8.0
B_2	3.2	2.2	60.8	24.4	9.4
C_1	2.8	2.4	28.4	49.6	16.8
C_2	4.4	3.2	56.8	30.4	5.2

Temporary mounts were made in an oil having the index of quartz, 1,544. In studying the minerals by means of the petrographic microscope, the following observations were made, where possible, to differentiate the various mineral species: color, refringence, birefringence, pleochroism, cleavage, form, twinning, extinction angles, interference figures, and signs. The approximate refractive indexes of the minerals were found by making temporary mounts in oils of different indexes. The color of opaque minerals was observed by means of reflected light. For details of the technic, description, and optical properties of minerals, the reader is referred to Fry (6), McIlvaine-Luquer (18), Rogers and Kerr (28), and Winchell (37).

Table 7 contains data of the minerals identified in the silt fractions from the various horizons in the Catalina clay profile. A kaolinlike mineral was identified on the basis of the suggestion of Ross and Kerr (29) that it, unlike the other stained minerals, is pleochroic when stained with dyes. A malachite green solution, used as a dye, was prepared by diluting one drop of a 5 per cent solution with 20 cc. of distilled water. The colors of the stained kaolinlike mineral turned from green to plum with rotations of the microscope stage.

Muscovite, quartz, and serpentine, the most abundant minerals, are largely in the specific gravity group 2.5–2.7 but are also present in the other groups. The C_2 horizon, however, contains less muscovite and quartz than the other horizons. The accessory minerals consist largely of the heavy minerals: rutile, augite, leucoxene, zircon, magnetite, sericite, and calcite; and of the lighter minerals: andesine, glass, gibbsite, and a kaolinlike mineral. The

TABLE 7

Minerals identified in the specific gravity groups of the silt fraction of Catalina clay*

HORIZON	SPECIFIC GRAVITY GROUP	RUTILE	AUGITE	LEUCOXENE	ZIRCON	MAGNETITE	CHLORITE	MUSCOVITE	QUARTZ	EPIDOTE	SERPENTINE	SERICITE	CALCITE	TALC	GLASS	ANDESINE	GIBBSITE	KAOLINLIKE MINERAL
A_1	>2.98	xx	x	x	x	x	...	....	....	....	....	....	....	....	....	....	....	...
A_2	.....	xx	x	x	x	x	x	x	Tr.	Tr.	....	....	....	....	....	....	....	...
B_1	.....	xx	x	x	x	x	x	x	Tr.	Tr.	....	....	....	....	....	....	....	...
B_2	.....	xx	...	x	.....	.....	x	x	....	....	x	....	....	....	....	....	....	...
C_1	.....	x	...	....	.....	.....	x	x	....	....	x	....	....	....	....	....	....	...
C_2	.....	x	x	....	.....	.....	x	....	....	....	....	....	....	....	....	....	....	...
A_1	2.70–2.98	....	....	....	.....	.....	x	x	x	....	x	x	x	....	....	....	....	...
A_2	.....	....	....	....	.....	.....	x	x	x	....	x	x	x	....	....	....	....	...
B_1	.....	....	....	....	.....	.....	x	x	x	....	x	x	x	....	....	....	....	...
B_2	.....	....	....	....	.....	.....	x	x	x	....	x	x	x	....	....	....	....	...
C_1	.....	....	..	....	.....	.....	x	x	x	....	x	x	x	....	....	....	....	...
C_2	.....	....	....	....	.....	.....	xx	xx	x	....	xx	...	x	....	....	....	....	...
A_1	2.50–2.70	....	....	....	....	....	...	xxx	xxx	....	xxx	....	....	....	...	x	....	...
A_2	.....	....	....	....	.....	.....	...	xxx	xxx	....	xxx	....	....	....	...	x	....	...
B_1	.....	....	....	....	.....	.....	...	xxx	xxx	....	xxx	....	....	....	...	x	....	...
B_2	.....	....	....	....	.....	.....	...	xxx	xxx	....	xxx	....	....	....	...	x	....	...
C_1	.....	....	....	....	.....	.....	...	xxx	xxx	....	xxx	....	....	....	...	x	....	...
C_2	.....	....	....	....	.....	.....	...	....	x	....	xxx	....	....	....	x	....	....	...
A_1	<2.50	....	....	....	....	....	...	x	....	....	x	....	....	....	x	...	x	x
A_2	.....	....	....	....	.....	.....	...	x	....	....	x	....	....	....	x	...	x	x
B_1	.....	....	....	....	.....	.....	...	x	Tr.	....	x	....	....	Tr.	x	...	Tr.	x
B_2	.....	....	....	....	.....	.....	...	x	Tr.	....	x	....	....	Tr.	x	...	Tr.	x
C_1	.....	....	....	....	.....	.....	...	x	Tr.	....	x	....	....	Tr.	x	...	Tr.	x
C_2	.....	....	....	....	.....	.....	...	x	Tr.	....	x	....	....	Tr.	x	...	Tr.	x

* x = little; xx = appreciable; xxx = abundant; Tr. = trace.

heavier minerals and gibbsite are more abundant in the solum than in the parent material.

DISCUSSION OF RESULTS WITH CATALINA CLAY

The consolidated parent rock of Catalina clay, according to its mineralogical composition, is an andesitic tuff. It contains abundant augite, which is essen-

tially a metasilicate of lime, magnesia, and ferrous iron, plus silicates of ferric iron and alumina. Augite is a ferromagnesian mineral and an important member of the pyroxene group. The presence of the secondary minerals serpentine, calcite, and chlorite indicates that this rock is a product of metamorphism. The plagioclase feldspar which occurs in this rock is andesine, which has been considerably altered through weathering processes. A characteristic of this rock is the absence of quartz.

This andesitic tuff is basic in reaction, pH 8.2 (table 5). It has given rise to an acid parent material (pH 4.4), that is, the C_2 horizon, rich in clay, total magnesia, and free iron oxide and alumina, but poor in free silica (tables 1 and 2). In passing from solid rock to parent material of Catalina clay, laterization is already pronounced and may thus be considered to be very largely a geologic process rather than a soil-building process. The weathering of the andesitic tuff released a large amount of magnesium, calcium, and sodium. The alkaline reaction of the medium in the early stages favored the precipitation of the soluble sesquioxides and the solution of silica. The presence of considerable easily soluble sodium in the early stages of weathering was probably a factor in increasing the solubility of silica. The humid climate provided sufficient precipitation to wash away from the soil parent material a large amount of bases and soluble silica.

The C_2 horizon has the highest contents of total and free iron oxide. The C_1 horizon has the highest contents of free silica, free alumina, and exchangeable hydrogen. The B_2 horizon has the highest content of coarse clay. These high contents are the result of the hydrolysis of augite in the B_2 and C_1 horizons. This is indicated by the absence of augite in these two horizons. The presence of this mineral in the A_1, A_2, and B_1 horizons, on the other hand, may be due to the formation of secondary augite in those horizons or to less favorable conditions for the hydrolysis of augite. Ferrous iron is probably set free in the B_2 and C_1 horizons, and, because of poorer conditions of oxidation at that depth, it moves down to the lower portion of the C_2 horizon where, because of less acid conditions, it is precipitated and oxidized as hydrated ferric oxide.

The percentages of free and total iron oxide and alumina rise regularly from the B_2 to the A_1 horizons. The percentages of free and total iron oxide rise also from the C_1 to the B_2 horizons. There is little evidence of the leaching of silica from the solum (tables 1 and 2). Sesquioxides have accumulated in the upper horizon, not solely because silica has been leached in the earlier stages of rock weathering, but because of further dehydration of hydrated sesquioxides in the upper solum where dryness is more effective because of higher temperatures. This is corroborated by the presence of magnetite in the upper three horizons and by its absence in the lower horizons. Catalina clay is a permeable soil because the large amount of hydrated and nonhydrated sesquioxides in the clay complex tend to keep it flocculated.

The rapid mineralization of organic matter is not a factor in laterization. The bulk of the soluble silica was leached, not because of the alkaline hydrolysis

resulting from the complete decomposition of organic matter, but because it was removed during the laterization of the andesitic tuff. The rapid mineralization of organic matter is, however, a factor in supplying bases for the solum.

The silt and coarse clay increase, and the fine clay decreases, both in quantity and exchange capacity, with solum depth. This is to be expected because of the more active disintegration of coarser particles in the A horizon. The active bases in the upper solum tend to flocculate the exchange material of the fine clay. As a result of this, much of the exchange material of the fine clay probably precipitates in the upper solum. The exchange capacity of the soil as a whole (table 4) appears to be unaffected by this process.

The exchange capacity of this soil is very low, only 6–10 m.e. A kaolinlike mineral identified in the quartz fraction of coarse and fine clay portions may be the seat of this exchange capacity. This kaolinlike mineral, however, was not found to be so abundant as muscovite, which is known to have slight but appreciable exchange capacity. There is a difference of 3 m.e. in the exchange capacity of horizons C_1 and C_2, in favor of the former (table 4), and muscovite was found to be more abundant in the former (sp. gr. 2.5–2.7, table 7). The material which gives rise to the exchange capacity of this soil thus appears to be a kaolinlike mineral and muscovite.

It is rather significant that muscovite is largely in the specific gravity group 2.5 to 2.7. It is also present in the specific gravity group of less than 2.5. According to Winchell (37) the specific gravity of muscovite ranges between 2.76 and 3.00. It seems, therefore, that hydration has affected this residual mineral. Muscovite has also been partly altered to sericite, a secondary muscovite, in all the soil horizons except the C_2. Traces of talc with a specific gravity of less than 2.5 were found in the B and C horizons. Talc was also found in the C_2 horizon as a heavy mineral having a specific gravity greater than 2.98. The specific gravity of talc, according to Winchell (37), ranges between 2.7 and 2.8. It seems, therefore, that the talc identified here as such has been considerably affected by weathering.

The bulk of the silt fraction is made up of the lighter minerals (table 6), largely muscovite, quartz, and serpentine (table 7). It must be pointed out, however, that the light mineral gibbsite and the heavy iron minerals were less abundant in the material examined, because most of the hydrated alumina minerals and all of the hydrated iron oxide minerals were destroyed, previously, by the drastic sodium sulfide-oxalic acid and sodium carbonate treatments. Magnetite and rutile were found to be present because they are resistant to the chemical treatment. Diaspore, Al_2O_3, was found to be absent in the soil profile. Chlorite and calcite are distributed throughout the profile. Quartz is very abundant throughout the soil profile except in the C_2 horizon. It is present as secondary quartz, since the original andesitic tuff had no quartz. A little andesine is present in all of the horizons except the C_2.

Catalina clay is a lateritic soil having as constituent minerals hydrated iron

oxides, gibbsite, muscovite, secondary quartz, serpentine, and, as accessory minerals, rutile, augite, leucoxene, zircon, magnetite, chlorite, sericite, calcite, glass, andesine, a kaolinlike mineral, and traces of talc and epidote. The hydrated iron oxides and gibbsite constitute from 18 to 24 per cent of the soil body. The accumulation of these resistant or inert minerals points to a severe weathering process.

To gain further information relative to the contention that laterization is largely a geologic process rather than a soil-building process, certain additional tests were made of soil profile samples of other lateritic soils from Puerto Rico, and of the parent material of the Catalina clay as well as that of two other lateritic soils and also of a nonlateritic soil.

REACTION OF VARIOUS HORIZONS OF OTHER LATERITIC SOILS

It was considered of importance to determine the effect of weathering in the profile of other lateritic soils. Determinations of pH, for the various soil horizons, were made colorimetrically with Truog's soil reaction tester. Table 8 contains pH data for the profile of seven lateritic soils from Puerto Rico located in the humid northern section of the Island. The data indicate that the rocks are neutral or alkaline, whereas the parent soil materials (horizon C_1) have, in most cases, already become strongly acid.

SOLUBILITY OF SILICA IN PARENT ROCKS OF LATERITIC AND NONLATERITIC SOILS

The following tests were made to find out whether soluble silica is released more rapidly from rocks which give rise to lateritic soils than from rocks which do not give rise to these soils.

Three consolidated parent materials of upland lateritic soils and one of a nonlateritic soil, in Puerto Rico, were chosen for this work. The lateritic soils are represented by an andesitic tuff, a serpentine rock, and a granitoid or granitelike rock; and the nonlateritic soil is represented by a quartz diorite. The rocks were ground in a steel mortar and sifted through a 160-mesh sieve. The parent material (horizon C_2) of Catalina clay was also included in the tests. In each case, a 0.1-gm. portion of the material was transferred to a liter Florence flask, and then a liter of distilled water was added. To a second similar set, carbonated water was added in place of distilled water. The flasks were stoppered and shaken for 1 day in an end-over-end shaker, after which portions of the supernatant liquid in each instance were clarified by centrifuging with an angle head for 10 minutes at 3600 r. p. m.

Soluble silica was then determined colorimetrically by means of the yellow color which developed on the addition of molybdate ions in a slightly acid solution as described by Snell (33, p. 517–525). It was found that the effect due to phosphorus is kept under control when the solution is brought to pH 1.5. The procedure used was as follows: A volume of 100 cc. of extract was evaporated to about 10 cc.; the pH was brought to 1.5 by adding 0.05 *N* HNO_3;

the color was then developed by adding 2 cc. of a 10 per cent solution of ammonium molybdate; and dilution was brought to 50 cc. for final comparison of color with that of a standard silica solution, in Nessler tubes. This method was checked gravimetrically, 500 cc. of the extract, which served also for the determination of soluble salts, being used. Phosphorus was also determined colorimetrically by the molybdate-blue method as a further check on its possible interference. The pH of the extracts was determined colorimetrically. The presence of iron was tested by evaporating a 50-cc. aliquot of the extract to about 5 cc., acidifying with two drops of HCl (1–1), and then adding two drops of a 2 per cent solution of potassium thiocyanate. Results, reported

TABLE 8

Reaction of different horizons of a number of lateritic soils from Puerto Rico

COTO CLAY			MATANZAS CLAY			ESPINOSA SANDY CLAY			BAYAMON CLAY		
Depth	Horizon	pH	Depth	Horizon	pH	Depth	Horizon	pH	Depth	Horizon	pH
inches			*inches*			*inches*			*inches*		
0–7	A	5.5	0–12	A	7.3	0–8	A	5.5	0–10	A	5.2
7–17	B	6.0	12–21	B_1	6.7	8–15	B	4.3	10–28	B	6.0
.....	..	...	21–34	B_2	6.5	.....	..	...	.....	..	...
17–40	C_1	8.0	34–48	C_1	6.3	15–36	C_1	4.3	28+	C_1	4.5
Limestone	D		Limestone	D		Limestone	D		Limestone	D	

NIPE CLAY			ALONSO CLAY			ALONSO CLAY, SMOOTH PHASE		
Depth	Horizon	pH	Depth	Horizon	pH	Depth	Horizon	pH
inches			*inches*			*inches*		
Iron nodules at surface	..	5.7	.....	..	...	.....	..	...
0–36	A	5.3	0–18	A	4.8	0–10	A	6.2
36–56	B_1	5.5	18–24	B	4.8	10–24	B	6.0
56–68	B_2	6.0	.....	..	...	.....	..	...
68+	C_1	6.2	24	C_1	4.8	24–36	C_1	4.4
Serpentine rock	D	7.8	Purple igneous rock	D	7.0	Purple igneous rock	D	7.0

in table 9, indicate that the silica of the parent rocks of the lateritic soils investigated was more subject to solution and leaching in water than was the silica of a parent rock (quartz diorite) of a nonlateritic soil. In carbonated water, however, the silica of the latter rock was as soluble as that of the former rocks. But carbonated water was more effective in extracting iron from parent rocks of lateritic soils bearing ferromagnesian minerals than from a parent rock (quartz diorite) of a nonlateritic soil.

GENERAL DISCUSSION

The pH data reported in table 8 indicate that the parent rocks of lateritic soils, in general, are basic in reaction but that some may have a neutral reac-

tion. The disintegrated parent materials (horizon C_1) are generally acid in reaction, except for Coto clay which is alkaline because of the presence of limestone particles. The disintegrated parent materials of these soils appear to be high in sesquioxides, as is that of Catalina clay.

Results given in table 9 indicate that the silica of the parent rocks of the lateritic soils investigated is more subject to solution and leaching in water than is the silica of a parent rock (quartz diorite) of a nonlateritic soil. In carbonated water there was not much difference in solubility of silica between the two parent-rock types, but it must be remembered that the percolating waters of these soils are probably, for the most part, low in their content of carbonic acid. The solvent action of the carbonated water was greater than that of the water alone in all cases, with the exception of serpentine. The water extracts had a pH around 5.2, whereas the carbonated extracts had a

TABLE 9

Solubility in water and in carbonated water of silica, phosphorus, iron, and total constituents of parent rock materials of lateritic and nonlateritic soils and pH of extracts

PARENT MATERIAL	WATER EXTRACT						CARBONATED WATER EXTRACT						
	pH	Dissolved					pH		Dissolved				
		Total constituents	SiO_2		P	Fe	Before boiling	After boiling	Total constituents	SiO_2		P	Fe
			Colorimetrically	Gravimetrically						Colorimetrically	Gravimetrically		
		per cent	*per cent*	*per cent*	*per cent*	*per cent*							
Andesitic tuff	5.2	6.8	1.2	1.6	0	0	4.6	6.6	19.2	3.2	4.8	0.016	little
Serpentine rock	5.4	10.0	4.8	4.4	0	0	4.2	6.8	6.8	3.8	1.4	0.0	0
Granitoid	5.0	4.6	1.0	1.0	0	0	4.2	6.2	8.0	0.4	2.0	0.034	little
Quartz diorite	5.2	3.6	0.0	0.0	0	0	4.2	5.6	14.2	3.5	4.2	0.024	trace
Catalina C_2	5.2	2.8	2.2	2.0	0	0	4.2	6.0	5.0	2.4	2.6	0	0

pH around 4.2. Boiling the latter increased the pH somewhat. Carbonated water extracted also more iron from two parent rocks (andesitic tuff and granitoid) of lateritic soils than from the parent rock (quartz diorite) of a nonlateritic soil. Carbonated water was found to be ineffective in extracting iron and phosphorus from the serpentine rock.

A better picture of the rocks is obtained by studying their mineralogical composition. The andesitic tuff has already been discussed. The serpentine rock contains mainly serpentine, bastite, minute grains of magnetite and chromite, and secondary iron oxides, principally limonite. The granitoid contains quartz, feldspar, biotite, and muscovite. The quartz diorite contains abundant quartz and also plagioclase feldspar and hornblende. The quartz diorite rock is basic in reaction, pH 8.0, and gives rise to traces of iron in the carbonated water extract. It does not weather into a lateritic soil, however,

because the bulk of its silica is not readily soluble. The granitoid rock is neutral in reaction, pH 7.0, and gives a test for iron in the carbonated water extract. It weathers, under humid tropical conditions, into a lateritic soil because it contains abundant bases and considerable easily soluble silica. The serpentine rock is basic in reaction, pH 7.8, but does not give a test for iron in the carbonated water extract. This rock is derived from a peridotite containing augite and olivine, ferromagnesian minerals that weathered into serpentine, magnetite, chromite, and secondary iron oxides, principally limonite. Laterization of serpentine releases a large amount of bases and soluble silica, which are washed away by the tropical rains. The hydrated and nonhydrated iron oxides remain in place to form a part of the parent material of the Nipe laterite.

Under humid tropical conditions, limestone weathers into lateritic soils when it contains considerable hydrated or nonhydrated oxides of iron and is low in silica. Laterization of limestone releases soluble calcium bicarbonate and leaves in place the oxides of iron. As the silica content increases, laterization is retarded because part of the lime may remain in place as insoluble calcium silicate.

The additional tests made on the reaction of various horizons of seven lateritic soils and on the water solubility of silica in parent materials of three lateritic soils and of a nonlateritic soil confirm the contention that laterization is largely a geologic process rather than a pedologic process.

Since laterization thus appears to be largely a process of mere physical and intense chemical weathering rather than a soil building or so-called pedologic process, and since there are no true horizons of eluviation and illuviation, these lateritic soils might better be looked upon as having only an A horizon consisting of the A_1 which contains some organic material and which grades into the A_2 horizon, extending virtually to the solid rock. The podzolization process is so limited under intense laterization that typical soil profiles are not usually developed.

SUMMARY

The nature of laterization has been investigated as revealed by chemical, physical, and mineralogical studies in the various horizons of a 20-foot profile of Catalina clay, an upland residual lateritic soil from Puerto Rico. The free silica and sesquioxides were extracted by special methods prior to the mechanical separations into sand, silt, and coarse and fine clay fractions. The silt and coarse clay were further separated into convenient specific gravity groups to facilitate the identification of the minerals by petrographic methods. Additional tests were made on the reaction of various horizons of seven lateritic soils and on the solubility of silica in parent rocks of three lateritic soils and of a nonlateritic soil. The results obtained may be summarized as follows:

In the formation of Catalina clay, an andesitic tuff, which is a basic rock rich in ferromagnesian minerals and containing some plagioclase feldspar, has been laterized into an acid

parent material rich in clay, total magnesia, and free iron oxide and alumina, but poor in free silica and bases. The weathering of the rock released a large amount of magnesium, calcium, and sodium. The alkaline reaction of the rock and of freshly weathered material has favored the precipitation of the sesquioxides and the solution of silica. The presence of considerable easily soluble sodium in the early stages of weathering was probably a factor in increasing the solubility of silica. The humid climate provided sufficient precipitation to wash away from the parent soil material the bulk of bases and soluble silica resulting from the laterization process.

It was found by chemical means that free iron oxide and free alumina constitute 18 to 24 per cent of the soil body of Catalina clay.

Sesquioxides have accumulated in the upper horizon of Catalina clay, not solely because silica has been leached in the earlier stages of rock weathering, but because of further dehydration of hydrated sesquioxides in the upper solum where oxidation conditions are better. Catalina clay is a permeable soil because the large amount of hydrated and nonhydrated sesquioxides in the clay complex tends to keep it flocculated.

The clay content of Catalina clay is very high, varying between 70 per cent in the C_2 and 87 per cent in the A_2 horizon. The silt and coarse clay increase somewhat, and the fine clay decreases, with solum depth. This is to be expected in view of the more active disintegration of silt and coarse clay particles in the upper solum.

Rapid mineralization of organic matter is not an important factor in laterization but is a factor in supplying bases for the solum.

The pH of Catalina clay rises from 4.4 in the parent soil material to 6.4 in the A_2 and 5.3 in the A_1 horizon. About three-fourths of the exchange capacity of the solum is saturated equally with calcium and hydrogen.

The exchange capacity of Catalina clay is rather low, only 6 to 10 m.e. The exchange capacity of the silt fraction increases from 4 to 9 m.e. and that of the coarse clay from 7 to 11 m.e., with solum depth, whereas that of the fine clay decreases from 10 to 2 m.e. It appears, therefore, that the active disintegration of the silt and coarse clay particles in the upper solum lowers also their exchange capacities. The active bases in the upper solum tend to flocculate the exchange material of the fine clay. As a result, much of the exchange material of the fine clay is probably deposited in the upper solum. The low exchange capacity of the soil as a whole is due either to a small amount of true base exchange material or else to material like muscovite, and the kaolinlike minerals, which have appreciable but low exchange capacity.

Specific gravity separations of the silt fraction of Catalina clay revealed that the bulk of the soil minerals have specific gravities ranging from 2.5 to 2.7.

The constituent minerals of the solum of Catalina clay are hydrated iron oxides, gibbsite, muscovite, secondary quartz, and serpentine. The accessory minerals are rutile, augite, leucoxene, zircon, magnetite, chlorite, sericite, calcite, glass, andesine, a kaolinlike mineral, and traces of talc and epidote. The accumulation of these resistant or inert minerals points to a severe weathering process.

In the eight lateritic soil profiles investigated, it was found that the parent rocks were neutral or alkaline, whereas the parent soil material (horizon C) had, in most cases, already become strongly acid and highly laterized, indicating that the laterization process is largely geologic rather than pedologic.

The silica of the parent rocks of the lateritic soils investigated was more subject to solution and leaching in water than was the silica of a parent rock (quartz diorite) of a nonlateritic soil. In carbonated water there was not much difference, but it must be remembered that the percolating waters of these soils are probably, for the most part, low in their content of carbonic acid.

Laterites are products of humid tropical weathering of rocks which are usually basic in reaction, resulting in acidic material high in free sesquioxides, low in free silica and exchange capacity, very permeable to water and air, and, in many instances, of great depth, but exhibiting little or no differentiation into soil horizons.

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EXPERIMENTS WITH BORON ON SOME NEW JERSEY SOILS[1]

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The numerous reports concerning the physiological importance of boron and its use in preventing certain diseases of plants, the recent widespread interest in its use in connection with fertilizers, and the need for definite information in regard to how crops respond to boron treatments on different types of soil, prompted this investigation. The object was to determine whether or not any soil and crop conditions in New Jersey require the use of boron, and, if the work showed increased yields from the use of boron, to make a careful study of the rate at which it should be used.

HISTORICAL

Since 1910 when Agulhon (1) demonstrated that wheat, oats, and radish require some boron for their normal development, numerous workers have shown the importance of this element in plant production. Maze (32), Warrington (47), Brenchley (6), Somner and Lipman (44), Somner and Sorokin (45), Johnston and his associates (22, 23, 24, 25), McHargue and Calfee (26), and McMurtrey (30) were among the later workers who were able to demonstrate that a wide variety of green plants are unable to complete their life cycle without at least a trace of boron.

Agulhon (1) and later Brenchley and Warrington (8) tried to explain the function of boron in the plant by noting the amounts of boron used, whereas others such as Haas and Klotz (16), Somner and Sorokin (45), Warrington (47), Johnston (22), Brenchley and Thornton (7), and Johnston and Dore (24) studied the cytological changes brought about by boron deficiencies in an effort to explain the role of boron. Warrington (47) and McHargue and Calfee (26) have attempted, without success, to substitute other elements for boron. More recently Schmucker (39) tried to explain the function of boron from experiments performed with pollen grains. Although these investigators have amassed many useful data, a completely satisfactory answer as to exactly why plants need boron is still lacking.

It was Brandenburg (5) who first demonstrated that a crop under field conditions could be suffering from a lack of boron. His work proved that dry or crown rot of sugar beets could be prevented by a sufficient supply of boron. This work has been substantiated by Rowe (37), Hanley and Mann (17), and Raleigh and Raymond (36). Hill and Grant (20) and Obrien and Dennis (34), working with sand and solution cultures, and later Macleod

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and Howatt (29) and Snyder and Donaldson (42), working with soil, have shown that boron is necessary to prevent black heart of turnips. The physiological disorders, drought spot and corky core, of apples have been treated successfully by McLarty (27), Hill and Davis (19), Degman and his associates (12), and Burrell (9), by applying a compound of boron to tree or soil. By addition of boric acid to the soil, McMurtrey (31) has succeeded in curing a disease of tobacco similar in appearance to the disease known as "topziekte." Purvis and Ruprecht (35) have found that borax will prevent the appearance of a physiological disease of celery known as cracked stems. Dearborn and his co-workers (10, 11) and Hartman (18) point to the fact that boron is essential in preventing browning of cauliflower. Besides the aforementioned diseases, a disease of spinach (18) and the yellows of alfalfa (28) may be due to an insufficient supply of boron.

It has been pointed out by various workers that certain conditions in the soil help to bring about boron deficiencies. Hill and Davis (19) found that corky core and drought spot of apples were prevalent on high carbonate lime soils. Obrien and Dennis (34) came to the same conclusion about black heart of turnips. Bobko and his co-workers (4) have shown that the ill effects of overliming can be corrected by additions of boron to the soil. Naftel (33) found that whenever he completely saturated the soil with calcium he obtained boron deficiencies. Hartman (18) strikes a discordant note by claiming that browning of cauliflower occurs more often in soils which are distinctly acid. Other factors which have been suggested as influencing boron availability are moisture and nitrogen level.

Several reasons have been advanced to explain why soils under field conditions show boron deficiency. Dennis and Obrien (14) think that soils originally low in boron or soils which have been cropped and leached continuously without replacement of boron may become boron deficient. Solunskaya (43) claims that the extensive development of leaves of plants grown on soils of high pH require a large amount of boron, and that soils having a high pH are most likely, therefore, to show boron deficiencies. Bobko and his co-workers (4) claim that boron deficiency is not due to chemical precipitation of boron but that boron is fixed by organisms taking part in the denitrification process which is hastened at the higher pH. Naftel (33), without presenting any specific data on this point, also discounts chemical precipitation and is inclined to agree with Bobko. Hartman (18) fails to suggest any reason why he found a greater number of boron-deficient plants on soils of low pH than on soils of high pH.

The effect of boron upon plants has been studied from another viewpoint, that of excesses or toxicity. Blair (2) and Blair and Brown (3) have shown the injurious results caused by excess borax, and Schreiner and his co-workers (38) have shown the ill effects of excess borax carried by certain potash salts. Eaton (15) and Scofield and Wilcox (40) have studied the effects of excess boron in irrigation waters. Eaton (15), Schreiner and his co-workers (38), and Weber (48) have described the boron toxicity symptoms of various plants, and Weber has made a detailed study of the internal anatomical changes produced by a toxic concentration of boron.

MATERIALS AND METHODS

Soils

Types and location. For pot experiments, soils were collected as follows: Sassafras loam from two different locations on the College Farm, Sassafras sandy loam from the vicinity of Bridgeton, Sassafras sand from the vicinity of Old Bridge, Collington sandy loam from the vicinity of Matawan, Colts Neck loam from the vicinity of Colts Neck, Dunellen sandy loam from Dunellen, and Hagerstown silt loam from the vicinity of High Bridge.

Methods of handling. The experiments with the different soils were performed in the greenhouse because of the ease in controlling conditions and in handling several soil types. In each case the soil was screened through a sieve of ¼-inch mesh and then thoroughly mixed before being placed in glazed pots. These pots, some of which were of 2-gallon capacity and others of 1-gallon capacity, had no drains.

Soil treatment

Lime, fertilizer, and borax applications to these soils were calculated on the weight basis, assuming 2,000,000 pounds of soil to the plowed acre.

Fertilizers. The fertilizers applied consisted of a solution of $(NH_4)_2SO_4$ and KH_2PO_4. Chemically pure salts were used to exclude the possibility of introducing boron with the fertilizers. An application equivalent to 1000 pounds of a 5–5–7 per acre for lettuce, beans, and radishes, and equivalent to 500 pounds for oats, was made before planting.

Lime. Because of reports of some response to boron applications on limed soils, the original plan was to adjust each type of soil to two different pH levels: the soil of section A to be at the field pH or adjusted to a relatively low pH, corresponding to that of soils in the state receiving no lime or very small applications; and the soil of section B to be limed to a pH of 6.0–6.6, corresponding to that of soils limed in accordance with good practice.

This plan was followed in the study of Collington sandy loam, Colts Neck loam, and Hagerstown silt loam (experiment 1). As the original pH of both samples of Sassafras loam was above 6.0, no attempt was made to study this soil at two pH levels. A further deviation from the plan followed in the raising of the pH of both sections of Sassafras sand above 7.0. A favorable response to borax in both sections of this soil suggested the possibility of obtaining beneficial results at high pH levels. The original plan was therefore modified to provide for the liming of section B to a pH above 7.0. This modified plan was followed in a second experiment with Hagerstown silt loam and in the study of Sassafras and Dunellen sandy loams.

The lime applied was a high calcium hydrated lime. In all cases it was mixed thoroughly with all the soil several days before planting of the crop.

Borax. Boron was supplied in the form of borax ($Na_2B_4O_7 \cdot 10H_2O$). This was dissolved in distilled water, and after it was applied the soil was flooded with distilled water to give an even distribution. The borax treatments were applied after the planting of each crop.

Other trace elements. No effort was made to supply any of the other trace elements, since it was assumed that the soil could supply these.

Growing of crops

In each section of the various soils, crops were grown with and without borax in triplicate pots. Crops were grown as season and conditions permitted.

On some soils several crops were grown. In watering plants only distilled water was used, each pot receiving the same amount. All crops were grown until they reached market size.

Statistical treatment

All yield values were treated statistically to enable the evaluating of response to treatment. In all treatments the following values were obtained: the mean (Mn) and its probable error (P.E.) and the standard deviation (σ) and its probable error (P.E.).

Whenever the significance of differences between means was in question, the existence of significance was determined by the Holzinger (21) test using the formula P.E. $(Mn_1 - Mn_2) = \sqrt{(P.E.\ Mn_1)^2 + (P.E.\ Mn_2)^2}$. The yields were classified as significant when the difference between the means of yields of the two treatments was at least four times the P.E. $(Mn_1 - Mn_2)$.

Analysis of plant material

The boron content of a number of plants was determined, to answer some of the questions raised. All plant samples were dried in the oven at about 70°C. and then were ground in a Wiley mill until the material would pass through a 1-mm. sieve. Composite samples of plants grown in the three pots of soil receiving the same treatment were prepared by the method of Delong (13) and were analyzed by the method of Smith (46), with the following exceptions: In most cases only 5-gm. samples, and in no case more than 10 gm., of oven-dried material were used. The HCl washings of the ignited material were not made up to 50 cc., but the boron content was determined by using an aliquot of 1 cc. from the combined filtrates. If the boron content was found too high for reading, the combined filtrates were diluted until 1 cc. of solution gave a boric acid concentration which could be determined by comparison with the set of standards (0.005 mgm.–0.04 mgm. of boric acid). In samples of plant material grown on soil not treated with borax no further dilution of the filtrates was necessary. In plants grown on soils treated with borax, however, it was found necessary to dilute the combined filtrates. Although Smith (46) claims that the reaction necessary to determine the boric acid takes place in 5 minutes, it was found necessary to allow all samples, after sulfuric acid and quinalizarin were added, to come to room temperature before reading. All readings were taken, therefore, after the samples had been standing for 30 minutes.

TECHNIC AND RESULTS OF INDIVIDUAL EXPERIMENTS

Sassafras loam

In one group of pots containing Sassafras loam, a crop of Scarlet Globe radish was grown on soil with 0, 10, and 20 pounds of borax per acre. This crop was followed by Big Boston lettuce, the borax treatments being repeated. In another group of pots, receiving similar borax treatments, a crop of Keystone

oats was follwed by a crop of Bloomsdale Long Standing spinach. Results are reported in table 1.

The results definitely show that radish, lettuce, oats, and spinach grown on this soil do not respond favorably to boron treatment. Applications of borax gave no increase in yield, and characteristic toxicity symptoms appeared on all crops grown with the 20-pound borax treatment. Despite these visual symptoms, lettuce was the only crop which gave a significant decrease in yield.

Sassafras loam from plot 7B

To study the response to borax by crops grown on a soil which had not been fertilized for many years, soil was obtained from plot 7B of the nitrogen availability series of field plots at the New Jersey Agricultural Experiment Station. This plot had received no fertilizer for 30 years but had received an application of 4000 pounds of limestone per acre every 5 years, except 1933 when the application of limestone was omitted. With the exception of slight modifications,

TABLE 1

Yields of crops on Sassafras loam

Mean weights in grams per pot

BORAX	RADISH		LETTUCE		OATS	SPINACH	
	Fresh Weight of Roots	Total Dry Weight of Roots and Tops	Fresh Weight of Tops	Dry Weight of Tops	Dry Weight as Hay	Fresh Weight of Tops	Dry Weight of Tops
lbs./A.							
0	21.60 ±0.66	4.10 ±0.14	102.00 ±3.35	10.17 ±0.18	20.50 ±0.44	32.20 ±0.88	4.27 ±0.02
10	23.10 ±2.17	4.30 ±0.23	104.30 ±5.15	10.83 ±0.40	20.80 ±0.24	28.30 ±0.92	4.03 ±0.13
20	22.70 ±1.76	4.28 ±0.10	89.30 ±4.06	8.17 ±0.13	21.30 ±0.56	29.70 ±0.94	4.60 ±0.14

a rotation of corn, oats, wheat, and 2 years of timothy has been used during the 30 years of continual experiments. In every case the crop has been removed.

In one group of pots containing this soil, Fordhook lima beans were grown with the following treatments of borax, 0, 2½, 5, 10, 20, and 40 pounds per acre. In another group of pots receiving the same tratments of borax, Keystone oats were planted. When the oats were removed the soil was planted to Scarlet Globe radishes, and the treatments of borax were repeated. All yields are given in table 2.

The results show that oats did not respond favorably even to the very small applications of borax, despite the fact that this soil had been cropped continuously for 30 years without any application of fertilizers. The yields of oats grown on untreated soil were at least equal to those of plants grown on borax-treated soils. The total dry weight of radish plants and beans, however, showed a significant beneficial response to an application of borax. Although the total dry weight of radishes was increased by an application of 2½ pounds

of borax and the total dry weight of beans increased by a 5-pound application, no further increases in yield were observed with the larger applications.

Toxicity of boron was observed on oats grown on soil with an application of 10 pounds of borax per acre. Such symptoms became increasingly severe as the amount of borax was increased. Beans showed slight toxicity with the 20-pound application of borax, and more severe symptoms were noted with the 40-pound application. The weights showed a marked reduction in yield with the 40-pound application. With radishes, slight toxicity symptoms appeared on plants grown with the 40-pound application of borax, but no decrease was noted in yield.

Collington sandy loam

A crop of Scarlet Globe radish, followed by a crop of Big Boston lettuce and later by Bountiful string beans, was grown in one group of pots. Treatments

TABLE 2

Yields of crops on Sassafras loam from plot 7B

Mean weights in grams per pot

BORAX	LIMA BEANS		OATS	RADISH		
	Fresh Weight of Beans	Dry Weight of Beans and Vines	Dry Weight of Hay	Fresh Weight of Roots	Fresh Weight of Tops	Dry Weight of Roots and Tops
lb./A.						
0	37.66 ±0.67	13.39 ±0.66	21.76 ±1.02	48.33 ±2.41	28.83 ±0.37	4.66 ±0.02
2.5	35.56 ±1.98	13.06 ±0.71	18.33 ±0.41	57.83 ±2.39	24.66 ±1.59	5.20 ±0.11
5.0	38.90 ±1.77	14.59 ±0.66	19.10 ±0.25	53.50 ±1.15	29.83 ±1.32	5.13 ±0.07
10.0	37.00 ±2.32	14.12 ±0.58	19.70 ±0.33	56.33 ±1.63	29.52 ±0.84	5.33 ±0.13
20.0	36.33 ±1.73	12.29 ±0.56	19.36 ±0.13	59.00 ±1.70	27.16 ±0.51	5.07 ±0.11
40.0	26.33 ±1.70	10.20 ±0.26	19.30 ±0.16	53.83 ±2.20	32.16 ±0.37	5.20 ±0.17

of 0, 10, and 20 pounds of borax were applied to both section A, containing the soil at the original pH of 5.90, and section B, containing the soil limed to a pH of 6.50. In another group of pots receiving similar borax treatments, a crop of Keystone oats was followed by a crop of Bloomsdale Long Standing spinach. The results are presented in table 3.

The results show that it was not necessary to add boron to this soil type for the crops grown. Toxicity symptoms were apparent on the 20-pound treatment with all crops.

Colts Neck loam

Lettuce and string beans were grown on one group of pots containing Colts Neck loam according to the plan followed with Collington sandy loam. Section A, with an original pH of 5.04, received no lime; section B was limed to a pH of 6.6. In another group of oats similarly treated, a crop of oats was followed by a crop of spinach. Results are given in table 4.

TABLE 3

Yields of crops on Collington sandy loam

TABLE 3

Yields of crops on Collington sandy loam

Mean weights in grams per pot

BORAX	RADISH		LETTUCE		STRING BEANS		OATS	SPINACH	
lbs./A.	Fresh Weight of Roots	Total Dry Weight of Roots and Tops	Fresh Weight of Tops	Dry Weight of Tops	Fresh Weight of Beans	Dry Weight of Beans and Vines	Dry Weight as Hay	Fresh Weight of Tops	Dry Weight of Tops
				Section A, pH = 5.90					
0	13.76 ±0.56	4.40 ±0.06	103.70 ±6.41	9.40 ±0.35	27.66 ±1.70	13.40 ±0.90	19.00 ±0.15	28.50 ±0.16	2.93 ±0.05
10	11.53 ±0.64	4.30 ±0.05	102.70 ±8.97	9.50 ±0.56	24.63 ±0.85	12.00 ±0.85	18.50 ±0.32	28.00 ±0.72	3.00 ±0.10
20	11.66 ±0.99	4.30 ±0.06	113.80 ±4.03	9.90 ±0.27	22.20 ±1.70	11.39 ±0.30	17.30 ±0.35	26.50*	2.95*
				Section B, pH = 6.50					
0	21.66 ±1.20	3.96 ±0.02	150.00 ±6.99	13.30 ±0.37	22.76 ±1.65	11.43 ±0.97	17.30 ±0.33	28.66 ±0.48	3.96 ±0.08
10	22.80 ±1.68	4.00 ±0.03	141.30 ±7.89	12.93 ±0.24	22.33 ±0.57	11.10 ±0.46	17.30 ±0.16	29.16 ±0.60	3.90 ±0.003
20	18.33 ±0.78	3.90 ±0.06	139.80 ±6.78	13.40 ±0.20	20.10 ±0.51	10.60 ±0.52	16.60 ±0.24	31.83 ±0.88	4.06 ±0.10

* Average of two samples.

TABLE 4

Yields of crops on Colts Neck loam

Mean weights in grams per pot

BORAX	RADISH		LETTUCE		STRING BEANS		OATS	SPINACH	
lbs./A.	Fresh Weight of Roots	Total Dry Weight of Roots and Tops	Fresh Weight of Tops	Dry Weight of Tops	Fresh Weight of Beans	Dry Weight of Beans and Vines	Dry Weight as Hay	Fresh Weight of Tops	Dry Weight of Tops
					Section A, pH = 5.04				
0	7.03 ±0.28	2.13 ±0.02	Crop failed to grow on this section		38.83 ±1.72	15.03 ±0.42	11.60 ±0.27	25.50 ±0.28	2.93 ±0.05
10	7.33 ±0.40	2.17 ±0.05			34.63 ±0.93	14.16 ±0.37	12.10 ±0.36	26.33 ±1.15	2.83 ±0.10
20	4.33 ±0.09	2.07 ±0.04			35.80 ±0.77	14.80 ±0.85	12.26 ±0.21	24.83 ±1.04	2.90 ±0.11
					Section B, pH = 6.60				
0	6.66 ±0.09	2.20 ±0.004	97.30 ±4.32	9.66 ±0.15	30.86 ±0.63	12.73 ±0.35	13.40 ±0.35	28.13 ±1.39	3.66 ±0.08
10	6.83 ±0.24	2.10 ±0.03	100.60 ±6.56	9.40 ±0.29	30.10 ±0.66	10.86 ±0.57	12.53 ±0.32	31.00 ±1.64	3.76 ±0.15
20	6.50 ±0.16	2.06 ±0.05	101.00 ±9.56	9.90 ±0.53	23.73 ±0.47	9.86 ±0.34	13.28 ±0.23	24.50 ±0.69	3.16 ±0.10

The results show that this soil type, like Sassafras loam and Collington sandy loam, required no addition of boron. As in the other soils, toxicity symptoms were quite apparent with the 20-pound borax treatment.

Sassafras sand

Since the original pH of the sample of Sassafras sand was 4.5, both sections were limed. Each pot in section A received the equivalent of 4000 pounds of lime per acre; and each pot in section B, the equivalent of 7000 pounds. This raised the pH of section A to 7.03 and that of section B to 7.66. Borax was applied to pots in each section as follows: 0, 2½, 5, 10, 20, and 40 pounds per

TABLE 5

Yields of radishes on Sassafras sand

Mean weights in grams per pot

BORAX *lbs./A.*	FRESH WEIGHT OF ROOTS	FRESH WEIGHT OF TOPS	DRY WEIGHT OF ROOTS AND TOPS
	Section A, pH = 7.03		
0	12.66 ±1.01	26.53 ±1.14	3.23 ±0.14
2.5	33.66 ±2.38	25.73 ±0.47	4.56 ±0.13
5.0	35.96 ±1.24	24.20 ±0.28	4.53 ±0.18
10.0	31.33 ±1.56	22.96 ±0.64	3.73 ±0.43
20.0	17.83 ±1.71	20.40 ±0.75	2.90 ±0.14
40.0	6.43 ±0.12	14.60 ±0.72	1.83 ±0.02
	Section B, pH = 7.66		
0	14.10 ±0.75	21.86 ±0.65	2.60 ±0.10
2.5	37.10 ±1.10	21.40 ±0.68	4.06 ±0.13
5.0	39.03 ±2.11	21.06 ±0.26	4.06 ±0.12
10.0	33.30 ±2.54	22.03 ±0.47	3.73 ±0.14
20.0	28.33 ±3.36	21.33 ±1.44	3.63 ±0.29
40.0	6.60 ±0.77	13.66 ±0.15	1.66 ±0.09

acre. Both sections were planted to Scarlet Globe radishes. Results are given in table 5.

The yield of radishes grown on Sassafras sand shows definitely the beneficial response of radishes to borax under certain conditions. This beneficial response was not evident in the weights of the leaves, but was quite evident in the weights of roots. The 2½-pound application of borax per acre increased the weight of roots, but further increases of borax did not markedly further increase the yield. In fact, mild signs of borax injury began to appear at the 20-pound application and became more severe with the 40-pound treatment. Practically identical results were noted in both sections.

Hagerstown silt loam

Experiment 1. Section A received no lime; each pot in section B received the equivalent of 2000 pounds of lime per acre. The following treatments were set up for each section: 0, 10, 20, and 40 pounds of borax per acre. All of the pots were planted to White Icicle radishes. The yields are shown in table 6.

Experiment 2. As soon as the radishes were harvested from both sections in experiment 1, an additional application of lime equivalent to 4000 pounds per acre was made to each of the pots of section B, raising the pH to 7.67. No lime was applied to section A. The borax and fertilizer treatments of

TABLE 6

Yields of radishes on Hagerstown silt loam

Mean weights in grams per pot

BORAX	EXPERIMENT 1			EXPERIMENT 2		
lbs./A.	Fresh Weight of Roots	Fresh Weight of Tops	Dry Weight of Roots and Tops	Fresh Weight of Roots	Fresh Weight of Tops	Dry Weight of Roots and Tops
	Section A, pH = 5.91			*Section A, pH = 5.82*		
0	28.30*	28.00*	5.10*	51.06 ±2.12	17.10 ±0.30	4.83 ±0.02
10	26.26 ±0.79	26.10 ±0.37	4.56 ±0.13	46.76 ±1.73	15.13 ±0.27	4.20 ±0.06
20	23.90 ±1.43	28.20 ±1.04	4.06 ±0.27	43.66 ±0.53	15.30 ±0.08	3.96 ±0.15
40	14.93 ±0.21	29.13 ±0.69	3.26 ±0.06	24.36 ±0.67	19.70 ±0.33	2.83 ±0.05
	Section B, pH = 6.58			*Section B, pH = 7.67*		
0	28.43 ±0.63	26.90 ±0.31	4.76 ±0.12	32.43 ±1.24	27.80 ±0.22	4.36 ±0.07
10	27.03 ±1.48	29.00 ±0.39	4.85 ±0.10	44.00 ±0.91	28.26 ±1.12	5.30 ±0.14
20	23.36 ±1.05	26.00 ±0.59	3.86 ±0.18	47.10 ±1.33	26.23 ±0.28	4.80 ±0.08
40	14.43 ±1.13	26.26 ±0.32	3.33 ±0.19	42.90 ±0.79	25.86 ±0.43	4.83 ±0.14

* Average of two samples.

experiment 1 were repeated, and all pots were replanted to White Icicle radishes. The results are given in table 6.

An analysis of the results of experiments 1 and 2 is extremely interesting. In the first experiment there was essentially no difference between plants grown on section A and section B. In both sections, plants grown on the untreated soil were the best. Slight toxicity was observed on plants in both sections when grown on soil receiving 40 pounds of borax per acre. In the second experiment, however, there was a clear-cut difference in response to borax, between the two sections. In this case, plants in section A showed no beneficial response to borax, and there were definite signs of toxicity with the 40-pound treatment and slight injury with the 20-pound treatment. In section B, plants grown on soil receiving no borax exhibited mild signs of boron deficiency. The leaves were small, and the roots were dull gray and showed cracking of the

epidermis. The 10-pound application of borax produced plants which were healthy in every respect. Plants grown with larger amounts of borax showed no marked increase over those with 10 pounds of borax. Another interesting observation was the fact that there were no signs of boron toxicity on any plants grown on section B. This fact supports the view that boron becomes less available at the higher pH levels.

Dunellen sandy loam

The original pH of Dunellen sandy loam was too low to grow satisfactory crops; therefore, section A, consisting of eighteen 2-gallon pots each containing 17 pounds of soil, was limed to a pH of 5.80 by an application of lime equivalent

TABLE 7

Yields of radishes on Dunellen sandy loam

Mean weights in grams per pot

BORAX *lbs./A.*	FRESH WEIGHT OF ROOTS	FRESH WEIGHT OF TOPS	DRY WEIGHT OF ROOTS AND TOPS
Section A, pH = 5.80			
0	87.50 ±2.52	45.16 ±2.54	12.90 ±0.08
2.5	76.83 ±3.22	49.00 ±0.66	12.50 ±0.25
5.0	75.33 ±3.40	51.66 ±0.39	12.70 ±0.01
10.0	87.88 ±2.16	48.50 ±1.59	13.30 ±0.23
20.0	75.33 ±2.80	48.66 ±1.79	12.53 ±0.37
40.0	50.83 ±5.93	42.83 ±2.54	10.40 ±0.77
Section B, pH = 7.06			
0	23.00 ±0.87	52.00 ±1.57	8.13 ±0.13
2.5	32.60 ±0.38	55.50 ±2.73	9.16 ±0.18
5.0	33.83 ±1.15	57.83 ±0.44	9.63 ±0.32
10.0	35.16 ±3.37	54.00 ±0.47	9.26 ±0.41
20.0	32.66 ±2.31	51.83 ±1.49	8.80 ±0.10
40.0	30.83 ±1.79	3.52 ±0.96	8.96 ±0.47

to 3000 pounds per acre. Section B, consisting of eighteen similar pots of soil, was limed to a pH of 7.06 by an application of 9000 pounds of lime per acre. The following treatments were set up in each section: 0, 2½, 5, 10, 20, and 40 pounds of borax per acre. All pots were planted to White Icicle radish. The results are given in table 7.

In section A, no beneficial response to borax was observed; there were definite signs of boron injury on plants grown with 40 pounds of borax per acre; and slight toxicity was observed with the 20-pound treatment. In section B there was a definite beneficial response to borax. The weights of roots were greatly increased by an application of 2½ pounds of borax per acre and were slightly further increased by an application of 5 pounds. The roots of plants in section

B receiving no borax were gray and rough. Although the yields on this section were better with borax than without borax, none of the yields were so good as those from section A.

Sassafras sandy loam

For section A, 12 pots were filled with Sassafras sandy loam without lime, and for section B, 12 corresponding pots were prepared and limed to a pH of

TABLE 8

Yields of radishes on Sassafras sandy loam

Mean weights in grams per pot

BORAX *lbs./A.*	FRESH WEIGHT OF ROOTS	FRESH WEIGHT OF TOPS	DRY WEIGHT OF ROOTS AND TOPS
Section A, pH = 5.45			
0	30.00 ±1.46	24.53 ±0.61	4.53 ±0.07
10	34.80 ±1.77	17.30 ±0.40	3.93 ±0.08
20	21.83 ±0.67	18.20 ±0.35	3.26 ±0.10
40	20.26 ±0.18	14.96 ±0.35	2.63 ±0.03
Section B, pH = 7.16			
0	23.36 ±2.35	17.73 ±1.33	3.30 ±0.27
10	28.80 ±1.78	19.56 ±0.60	3.90 ±0.16
20	31.46 ±0.45	13.96 ±0.33	3.40 ±0.05
40	26.66 ±1.41	15.53 ±0.77	3.30 ±0.04

TABLE 9

Boron content of plants as influenced by additions of borax to the soil

BORAX ADDITIONS TO SOIL	BORON CONTENT OF PLANTS						
	Oats	Spinach	Beans		Lettuce	Radish	
			Vines	Pods		Tops	Roots
lb./A.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
0	6	23	24	12	28	29	13
10	22	80	28	12	37	89	19
20	50	105	60	13	60	204	34

7.16. The following borax treatments were applied in each section: 0, 10, 20, and 40 pounds per acre. All pots were planted to White Icicle radish. Results are given in table 8.

On this soil, as on Sassafras sand, Hagerstown silt loam, and Dunellen sandy loam, there was evidence that the borax in some manner had become less available at the higher pH level. In section A, plants grown without borax produced healthy roots, whereas plants receiving 40 pounds of borax per acre showed signs of injury. In section B, plants grown without any borax had

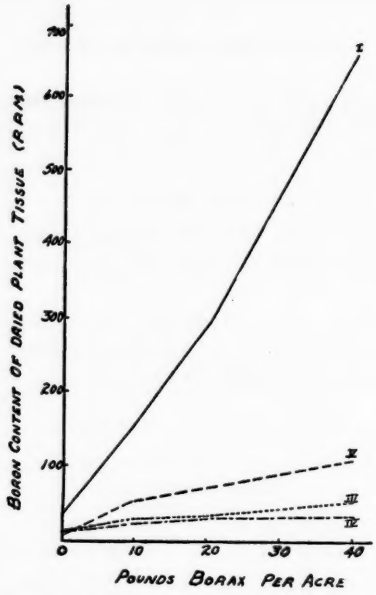

FIG. 1. BORON CONTENT OF RADISHES GROWN ON HAGERSTOWN SILT LOAM

Two applications of borax at the rate indicated, I, Leaves grown at pH 5.82; II, Leaves grown at pH 7.67; III, Roots grown at pH 5.82; IV, Roots grown at pH 7.67.

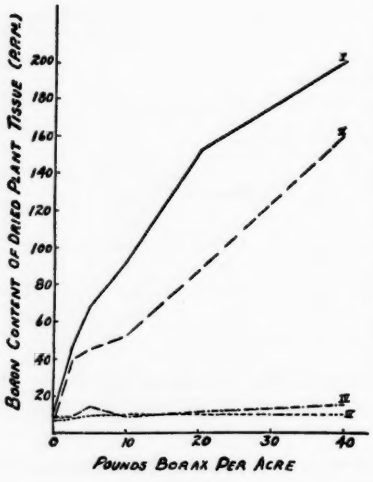

FIG. 2

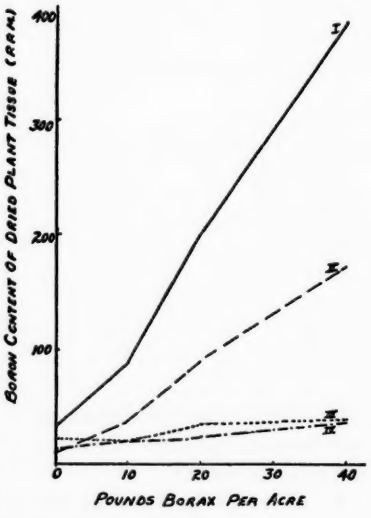

FIG. 3

FIG. 2. BORON CONTENT OF RADISHES GROWN ON DUNELLEN SANDY LOAM

I, Leaves grown at pH 5.80; II, Leaves grown at pH 7.06; III, Roots grown at pH 5.80; IV, Roots grown at pH 7.06.

FIG. 3. BORON CONTENT OF RADISHES GROWN ON SASSAFRAS SANDY LOAM

I, Leaves grown at pH 5.45; II, Leaves grown at pH 7.16; III, Roots grown at pH 5.45; IV, Roots grown at pH 7.16.

cracked, discolored roots; the plants receiving borax showed a small increase in size and were healthy in appearance. No plants in this section showed borax toxicity even with the 40-pound treatment.

ANALYSIS OF PLANTS FOR BORON

The results of the chemical analysis of plant materials, given in table 9, indicate that certain plants, at least, take up boron somewhat in proportion to the amount of available boron present. Evidently, this does not hold for roots of radishes or for the pods of beans, the amount of boron present varying only slightly regardless of whether the plant was grown in soil containing a small or a large amount of borax.

The effects of pH upon the availability of boron are clearly illustrated in figures 1, 2, and 3. The boron content of leaves of radish grown on Sassafras sandy loam and Hagerstown silt loam limed to a pH of about 7.2–7.7 was less than half the amount found in leaves of radish plants grown on these same soils at lower pH levels.

CONCLUSION AND DISCUSSION

Although this investigation is not complete, several interesting points are brought out.

The need for taking special care to provide additional boron in fertilizers is not a general problem for farmers working with soils similar to those used in this experiment.

Of all the soils tested at their original pH, only one (Sassafras loam from plot 7B) gave any beneficial response to applications of borax and then not for all crops grown on this soil. The response on this soil shows that it is possible to bring about mild boron deficiency in certain crops if the soil is continuously cropped and no boron supplied. Even when four of these soils (Colts Neck loam, Collington sandy loam, Dunellen sandy loam, and Hagerstown silt loam) were limed reasonably, they failed to give any beneficial response to borax. It was shown that all soils used, with the exception of Sassafras loam from plot 7B, were capable of producing good crops even though chemically pure salts were used as fertilizers and no borax was applied. At least several of these soils (Sassafras loam, Collington sandy loam, Colts Neck loam) were able to produce several crops with the use of fertilizers made from chemically pure salts, and with no additions of borax.

Although the application of boron is hardly a general necessity, it is possible under certain liming practices to bring about a condition which will be improved by applications of borax. Radish grown on all soils which had been limed to a pH somewhat above 7.0 showed an increase in root yield when borax was supplied. Plants grown on these soils at a high pH without borax developed mild boron deficiency symptoms. In no case were there any of the *marked* boron deficiency symptoms, such as death of the growing point of root and shoot, which have been noticed by observers working with sand and solution cultures.

The fact that a high pH is instrumental in making boron less available was clearly indicated by the *mildness* of the toxicity symptoms at the high pH levels studied. Boron toxicity on radish plants grown on these soils was for the most part very mild or absent even on plants grown on soil receiving 40 pounds of borax per acre. On the same soil at a lower pH, radish plants exhibited severe injury when grown with the 40 pounds per acre, and in some cases severe toxicity was apparent with the 20-pound application.

Chemical analysis of plant materials showed that the amount of boron in the plant is markedly increased as the amounts of borax added to the soil are increased. Roots of radish and pods of beans, however, are exceptions.

The analysis also proved that boron was made less available at the higher pH levels. In some cases the amount of boron in the plant grown at the high pH levels was less than half that in plants grown in the same soil at a lower pH and receiving the same amount of borax.

It must be remembered, however, that on most soils large amounts of lime were required to raise the pH high enough for crops to respond beneficially to borax. Such high pH values would be relatively rare in the soil types investigated. Also, in some cases 10 pounds of borax per acre was sufficient completely to rectify the boron deficiency, and in no case was there any extra beneficial response noted above the 20-pound treatment. As some fertilizers contain traces of boron (50, 41), it would not be advisable to apply more than 20 pounds of borax to the acre, even on soils limed to a high pH. Larger applications may injure sensitive plants.

SUMMARY

To determine whether the use of borax on certain soils would result in improved growth, crops were grown on eight different soils receiving fertilizers made from chemically pure salts and watered with distilled water.

Of the crops grown on six soils at their original pH values, only radishes and beans on Sassafras loam from plot 7B (nitrogen availability plots previously described) gave any beneficial response to borax.

Three soils, even when limed to a pH of 6.0–6.6, failed to give any beneficial response to borax.

Four soils, including one of those which had failed to give any beneficial responses when limed to a pH of 6.0–6.6, did give a beneficial response to applications of borax when limed to a pH >7.0.

Applications of borax on soils limed to a high pH (pH >7.0) markedly increased the root weight of radishes. In some cases a treatment of $2\frac{1}{2}$ pounds of borax per acre corrected the deficiency, and in no case were benefits noted beyond the 20-pound treatment per acre.

Boron is made less available on soils limed to a pH above 7.0. Besides the effects on yields, this was clearly shown by the fact that a greater amount of borax was necessary to cause toxicity of plants grown on soils at a high pH.

The boron content of plants grown on soils having a pH > 7.0 is less than that of plants grown on the same soil at a lower pH.

Plants grown on soils treated with borax show an increase in the boron content as the amount of borax applied to the soil is increased. Roots of radish and pods of beans, however, do not increase in boron content to any large extent as the borax concentration is increased in the soil.

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EFFECT OF APPLICATIONS OF MAGNESIUM ON CROP YIELDS AND ON THE PERCENTAGES OF CALCIUM AND MAGNESIUM OXIDES IN THE PLANT MATERIAL

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Magnesium is one of the elements essential for all crops. Until comparatively recently, however, it was assumed to be unnecessary to supply this element in the form of a commercial fertilizer, since, in general, normal soils contain a fair amount of magnesium and, further, because magnesium is supplied to many soils in the form of dolomitic limestone and in farm manure and may be present in small amounts in fertilizer materials.

MAGNESIUM IN NEW JERSEY SOILS

In general, the soils of New Jersey are fairly well supplied with magnesium (1, 2, 3). Soils like the Penn, Lansdale, Washington, Chester, Gloucester, Dutchess, Hagerstown, and Montalto in the northern part of the state commonly contain 1 per cent or more of MgO and, generally, a lower content of calcium. Of the Costal Plain soils, Collington and Keansburg are notably high in magnesium and in many places show higher percentages of magnesia than of lime. Lakewood and Sassafras sands are extremely low in both calcium and magnesium. Figure 1 indicates the relative amount of magnesia and figure 2 the relative amount of lime, in a few of the important soils of the state.

In recent years reports of magnesium deficiency in soils have come from several sections of the country, notably the potato sections of Maine and Virginia and certain tobacco sections in the South. Long-time experiments at this station with calcium and magnesium limestones have not indicated a definite magnesium deficiency in Sassafras loam which is being used for the growing of vegetables and general farm crops. Recently, however, yields of alfalfa and timothy from plots which have received magnesium limestone have been slightly better than yields from corresponding plots which have received calcium limestone, although no magnesium deficiency symptoms were apparent.[3]

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[2] The third author is now in soil work at Idaho Agricultural Experiment Station.

[3] The calcium limestone used during the early part of the work (1908 to 1918) contained about 1.25 per cent of magnesia; that used more recently, about 5.0 per cent magnesia.

SYMPTOMS OF MAGNESIUM DEFICIENCY

Magnesium is a constituent of the green coloring matter of plants. In soils deficient or very low in this element, the plant may not make normal growth.

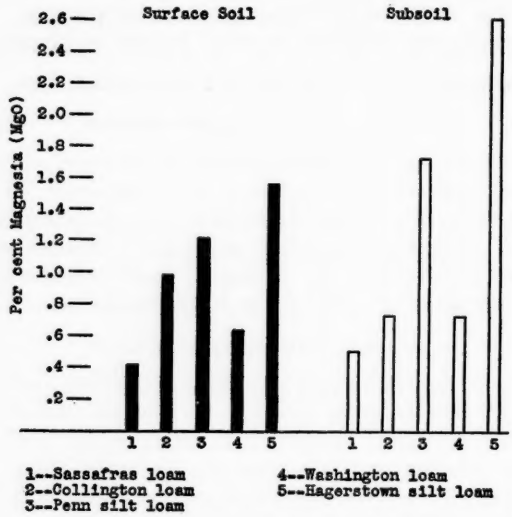

FIG. 1. PERCENTAGE OF MAGNESIUM OXIDE IN SOME LOAM SOILS OF NEW JERSEY

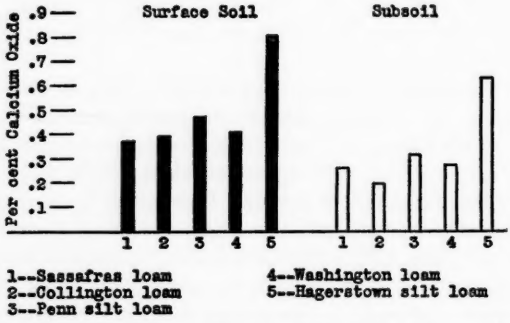

FIG. 2. PERCENTAGE OF CALCIUM OXIDE IN SOME LOAM SOILS OF NEW JERSEY

In describing magnesium deficiency symptoms in tobacco McMurtrey (11) says:

The specific symptom of magnesium hunger is the loss of the green color at the tip and margins of the lower leaves of the plant. This loss of color seems to advance toward the base of the individual leaf and may extend to the upper leaves of the plant depending upon

the acuteness of the deficiency. In some instances the entire lower leaves may be almost white when the trouble is first recognized, although the veins and mid-rib tend to retain their normal green color. The symptoms in the field are identical with those produced under controlled conditions.

Wallace (15) points out that the ratio of potassium to magnesium may be important in apple and raspberry growing in cases where manure is not procurable and the grower has to rely solely on the use of artificial manures, since magnesium deficiency results in very serious premature defoliation of these plants.

In their paper on the nutrition of apple trees, Blake, Nightingale, and Davidson (4) say:

When magnesium was withheld, a characteristic type of leaf injury soon developed and was followed by abscission of the affected leaves. The current stems of trees lacking magnesium were very low in carbohydrates, small in diameter, and deficient in woodiness.

In addition to using magnesium salts and dolomitic limestone in connection with the fertilizer treatment, Chucka (7) used magnesium as a spray on potato plants in Maine. Discussing the effects, he says:

In all cases marked response to added magnesium was noted in 5 to 10 days after the magnesium was added. The chlorotic leaves did not seem to regain their green color, but no more chlorosis developed on the old leaves after the addition of magnesium and all of the new growth had a healthy green appearance. In the fall the untreated plants died early while the treated plants remained green until killed by late blight or frost.

He also points out that the effect of the magnesium on yield of potatoes was surprisingly great.

Jacks and Scherbatoff (9) direct attention to the part which magnesium plays in the chlorophyll molecule and comment as follows:

Magnesium deficiency symptoms are probably the immediate result of an insufficiency of the element, and therefore of chlorophyll, in the plant, and the fact that the symptoms have been observed most frequently on light acid soils suggests that they are often related to a true magnesium deficiency in the soil, rather than to conditions rendering magnesium "unavailable." Magnesium is one of the most soluble and most weakly absorbed of the common exchangeable cations, and actual deficiencies in soils may be much more common than has yet been recognized.[4]

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[4] Evidence presented by Joffe, Kardos, and Mattson (Joffe, J. S., Kardos, L. T., and Mattson, S. 1935 The laws of soil colloidal behavior: XVII. Magnesium silicate—its base-exchange properties. *Soil Sci.* 40: 255–268), seems to indicate that magnesium is a strongly adsorbed cation and may be fixed in the soil possibly as magnesium silicates.

Prince and Toth (Prince, A. L., and Toth, S. J. 1937 Effects of long continued use of dolomitic limestone on certain chemical and colloidal properties of a Sassafras loam soil. Paper presented before Sec. 2, Soil Science Society of America, Chicago, Dec. 3, 1937), have shown that approximately 25 to 30 per cent of the total calcium in soils treated with dolomitic limestone was exchangeable by extraction with normal ammonium acetate, and that only 3 to 5 per cent of the total magnesium was exchangeable. They point out further that the amount of electrodialyzable calcium was similar to that extracted with normal

EXPERIMENTAL

Frequent inquiries with reference to the magnesium requirement of different crops indicated a need for work along this line. A series of pot experiments was started, therefore, in the fall of 1934 and continued throughout the winter. Greenhouse experiments were again conducted during the winter of 1935 and 1936; and outside experiments in cylinders and wooden forms and, to a limited extent, in the field, during the summers of 1936 and 1937.

The following soil types were used in this work: Sassafras loam, silt loam, sand, and fine sandy loam; Portsmouth loam; Collington loam; Penn loam and silt loam; Chester loam; Dunellen loam; Wethersfield loam. The field crops grown were buckwheat, rape, barley, corn, soybeans, and mixed hay. The vegetable crops were spinach, cabbage, radishes, beets, carrots, garden peas, string beans, tomatoes, and peppers, but not all crops were grown on all types of soil. In all cases where the soil was distinctly acid, calcium carbonate was added to bring the pH near to the point suitable for the crop to be grown. Also in all cases a complete fertilizer was used.

During the 3-year period over which this work extended, a large volume of data was accumulated. Very much of the work was negative, that is, in a good many cases the magnesium treatment resulted in some increase in yield, but in even more cases there was no increase or a decrease in yield as compared with the check treatment. The depression in yield was not generally of sufficient magnitude, however, to cause symptoms of magnesium toxicity. On the other hand, definite symptoms of magnesium deficiency were detected in one instance, with string beans on Sassafras sand[5] (plate 1).

Crop yields

In view of the somewhat negative results, it seems unwise to load this report with a large number of tables of weights of individual crops under the various treatments.[6] Tables showing yields on a few types of soil are given. These are more or less typical of results obtained with other crops and on other types of soil.

From a study of table 1, it is quite evident that the use of magnesium in pot experiments did not result in distinctly increased yields in very many cases. For soybeans and barley such increases as are noted are negligible. Carrots on Penn loam and Chester loam show increases with magnesium sulfate, but the same crop on Sassafras loam shows a decided decrease. String beans grown on Sassafras sand gave a distinct increase in yield with magnesium sulfate. In general, the use of the magnesium sulfate for vegetable crops resulted in about as many slight decreases in yield as increases. This does not neces-

ammonium acetate but that the value for electrodialyzable magnesium was only about 60 per cent of that obtained by the salt extraction method. They say, "The partial fixation of magnesium by silicates no doubt accounts for its incomplete removal by electrodialysis."

[5] This soil is very low in mineral nutrients.

[6] All the data are on file in the soil department and are available should they be called for.

sarily mean that the magnesium sulfate actually had a depressing effect but rather points to a negative effect as compared with the check treatment.[7]

In a further study of the influence of magnesium on crop yields, peppers were grown in 1935 and corn (as forage) was grown in 1936 on five types of soil. The soils (Portsmouth loam, Penn loam, Sassafras silt loam, Sassafras loam, and Sassafras sand) were placed in wooden forms 1 yard square with a soil depth of about 10 inches. For both peppers and corn two squares were left without magnesium, two were treated with magnesium sulfate ($MgSO_4 \cdot 7H_2O$) at the rate of 100 pounds to the acre, and two at the rate of 200 pounds. A

TABLE 1

Influence of magnesium on the yields of soybean hay, barley, spinach, carrots, and beets grown on different types of soils in pots

SOIL TYPE	MAGNESIUM TREATMENT	DRY WEIGHT		AS MARKETED		
		Soybean hay	Barley—grain and straw	Spinach	Carrots	Beets
		gm.	*gm.*	*gm.*	*gm.*	*gm.*
Sassafras loam	No magnesium	21.5	45.0	122	76	42
	2 gm. $MgSO_4 \cdot 7H_2O$	23.2	45.7	84	46	39
	4 gm. $MgSO_4 \cdot 7H_2O$	21.2	47.0	96	52	45
Penn silt loam	No magnesium	19.2	48.3	68	24	28
	2 gm. $MgSO_4 \cdot 7H_2O$	20.0	47.7	69	44	39
	4 gm. $MgSO_4 \cdot 7H_2O$	20.7	49.7	58	48	32
Chester loam	No magnesium	14.8	35.7	44	21	27
	2 gm. $MgSO_4 \cdot 7H_2O$	13.3	37.3	48	25	29
	4 gm. $MgSO_4 \cdot 7H_2O$	15.3	35.8	44	28	36
Dunellen loam	No magnesium	....	41.3	...	...	36
	2 gm. $MgSO_4 \cdot 7H_2O$	....	43.3	...	...	35
	4 gm. $MgSO_4 \cdot 7H_2O$	....	40.7	...	...	26
Wethersfield loam	No magnesium	10.0	37.3	32	...	23
	2 gm. $MgSO_4 \cdot 7H_2O$	9.7	37.7	34	...	32
	4 gm. $MgSO_4 \cdot 7H_2O$	9.7	36.7	32	...	29

4–8–6 fertilizer was used at the rate of 1000 pounds an acre, but only half was applied at the time of planting, the remaining half being applied July 16. For the corn in 1936 the magnesium application was increased to make it equivalent to 150 and 300 pounds to the acre. The fertilizer treatment was

[7] In connection with fertilizer experiments with potatoes in several localities in the state, the department of plant pathology has used magnesium in the form of the sulfate and also as Kieserite and as dolomitic limestone. On two farms there was a fair response to the magnesium treatments for two successive years. Aside from these two farms, no appreciable increase in yield has been noted.

the same as that for the peppers in 1935, except that half the amount was broadcast before planting and the remainder used as two separate side-dressings. The green weight of peppers and the dry weight of corn forage are shown in table 2. The figures show that the magnesium-treated soil did not give a pronounced increase in yield of either peppers or corn except on Sassafras sand, which is one of the poorest soils in the state and has a very low content of both calcium and magnesium.

In 1937 cabbage was grown on the five types of soil in these forms, with a continuation of the magnesium treatment. The crop was a failure on Sassafras sand, no marketable heads being produced. On Penn loam, Sassafras

TABLE 2

Influence of magnesium on the yields of green pepper and corn forage grown in wooden forms 3 feet square

SOIL TYPE	MAGNESIUM TREATMENT, ACRE BASIS	GREEN WEIGHT OF PEPPERS	DRY CORN FORAGE
		gm.	*gm.*
Portsmouth loam	No magnesium	1,855	1,286
	100 lbs. $MgSO_4 \cdot 7H_2O$	1,845	1,162
	200 lbs. $MgSO_4 \cdot 7H_2O$	2,026	1,060
Penn loam	No magnesium	2,384	793
	100 lbs. $MgSO_4 \cdot 7H_2O$	2,032	724
	200 lbs. $MgSO_4 \cdot 7H_2O$	1,417	756
Sassafras silt loam	No magnesium	2,545	849
	100 lbs. $MgSO_4 \cdot 7H_2O$	2,396	872
	200 lbs. $MgSO_4 \cdot 7H_2O$	2,184	905
Sassafras loam	No magnesium	2,482	882
	100 lbs. $MgSO_4 \cdot 7H_2O$	1,999	727
	200 lbs. $MgSO_4 \cdot 7H_2O$	2,555	776
Sassafras sand	No magnesium	1,131	486
	100 lbs. $MgSO_4 \cdot 7H_2O$	1,344	533
	200 lbs. $MgSO_4 \cdot 7H_2O$	1,317	595

silt loam, and Sassafras loam, the magnesium treatment gave no significant increases in yield over those without magnesium. On Portsmouth loam, the average yield was 1480 gm. of marketable heads per square (9 square feet) without magnesium treatment; the average yield was 2178 gm. per square for the four squares that received magnesium sulfate; but the yield with the double portion of magnesium sulfate was somewhat smaller than with the single portion.

In another experiment, tomatoes were grown on three types of soil (Sassafras loam, Sassafras sand, and Collington loam) placed in wooden forms having a surface area of 4 square feet. The soil in the forms had a depth of

about 10 inches. Three squares for each type of soil received no magnesium and three received the magnesium sulfate at the rate of approximately 600 pounds an acre. A 4–8–6 fertilizer was used at the rate of 1000 pounds an acre, one-half applied at the time of setting plants and one-half later. The magnesium treatments and the yields of tomatoes are indicated in table 3. From the table it will be seen that with each type of soil there was an increase in yield of tomatoes where magnesium sulfate was applied, the increase amounting to 16 per cent for Sassafras loam, 19 per cent for Sassafras sand, and 25 per cent for Collington loam.

In 1936 string beans were grown in three types of soil (Sassafras loam, Collington loam, and Sassafras sand) placed in wooden forms 2 feet square. A complete fertilizer was used at the rate of 1000 pounds to the acre. To three squares representing each type of soil no magnesium was applied and to three other squares for each type, magnesium sulfate was applied at the rate of 600 pounds an acre. With Sassafras loam and Collington loam the magnesium

TABLE 3

Influence of magnesium on the yield of tomatoes grown in wooden forms 2 feet square

SOIL TYPE	MAGNESIUM TREATMENT	RIPE FRUIT
		gm.
Collington loam	No magnesium	7,392
	25 gm. $MgSO_4 \cdot 7H_2O$	9,261
Sassafras loam	No magnesium	5,637
	25 gm. $MgSO_4 \cdot 7H_2O$	6,521
Sassafras sand	No magnesium	2,580
	25 gm. $MgSO_4 \cdot 7H_2O$	3,076

treatment had little effect on the yield. With Sassafras sand (very low in CaO and MgO) the three squares without magnesium gave a yield of 42 gm. of beans and 40 gm. of vines. The three squares with the magnesium treatment gave a yield of 64 gm. of beans and 116 gm. of vines. Plate 1 shows representative plants grown with and without magnesium.

Table 4 shows results obtained with mixed hay and with soybean hay, grown with different amounts of calcium and magnesium limestone on Sassafras loam in 1935 and 1936 respectively. The plots were 1/20 acre in size and had been under the limestone treatment since 1908, the applications being made at 5-year intervals up to 1928. Since that date no limestone has been applied. A moderate application of a complete fertilizer was made annually. Without exception, the yields with the magnesium limestone, as shown in table 4, are slightly higher than the yields with the calcium limestone. In six cases out of nine, however, the advantage of the magnesium limestone over the calcium limestone is less than 300 pounds of hay to the acre. In general

the pH of the soil on which the magnesium limestone is used is slightly higher than that of the soil on which the calcium limestone is used. This may account, in part, for the higher yields with the magnesium limestone.[8]

No general rule can yet be laid down for the use of magnesium, but where growers suspect magnesium deficiency it is safe to substitute dolomitic lime or limestone for calcium lime at intervals, as a matter of precaution. There need be no fear of injury from the *judicious* use of the dolomitic forms of lime. Where magnesium deficiency symptoms are detected, magnesium may be supplied in the form of the sulfate, dolomitic hydrate, or dolomitic limestone.

TABLE 4

Influence of magnesium on the yields of mixed grasses and of soybean hay grown on Sassafras loam in the field

Treatments and yields on acre basis

LIME TREATMENT	PLOT NUMBER	YIELD OF MIXED GRASS HAY	PLOT NUMBER	YIELD OF SOYBEAN HAY, SECTION 1	PLOT NUMBER	YIELD OF SOYBEAN HAY, SECTION 2
		lbs.		*lbs.*		*lbs.*
No lime	35	2,100	21	1,486	28	1,575
1,000 lbs. Calcium limestone	36	2,588	22	2,450	29	2,275
2,000 lbs. Calcium limestone	37	3,290	23	2,885	30	3,239
4,000 lbs. Calcium limestone	38	3,924	24	3,534	31	3,648
1,000 lbs. Magnesium limestone*	39	2,871	25	2,643	32	2,706
2,000 lbs. Magnesium limestone	40	3,819	26	3,569	33	3,547
4,000 lbs. Magnesium limestone	41	4,077	27	3,763	34	3,782

* About 30 per cent magnesia (MgO) and 20 per cent lime (CaO).

Lime and magnesia in the crops

In the course of the work it was observed that in the majority of cases the percentage of MgO in the plant material increased with the increase in the amount of magnesium applied. It was noted also that there was a tendency for the CaO to decrease as the MgO increased.

Other investigators have pointed out that application of magnesium compounds has increased the magnesium content of the plant. In connection with magnesium deficiency studies in vegetable production, Carolus and Brown (6) have pointed out that fruits (peppers, tomatoes, and eggplants) from magnesium-fertilized plants, contained 42 per cent more MgO than those from unfertilized areas, and Carolus (5) has shown a higher percentage of magnesium in potato plants grown with hydrated magnesium lime and dolomitic limestone than with calcium lime or no lime.

[8] A pound of pure magnesium carbonate, $MgCO_3$, has a slightly greater corrective effect than a pound of pure calcium carbonate.

Naftel (12) made a study of the effect of pure $CaCO_3$ and calcium-magnesium carbonate on the mineral content of sorghum grown on three types of soil. In each case the calcium-magnesium carbonate gave an increase in the percentage of magnesium in the plant material and a decrease in the percentage of calcium, as compared with the $CaCO_3$-treated plants.

Cunningham (8) found that applications of magnesium sulfate to pastures slightly increased the percentage of MgO in the dry matter.

TABLE 5

Influence of magnesium on the percentages of CaO and MgO in spinach grown on different types of soils

Dry matter basis

MAGNESIUM TREATMENT	PENN SILT LOAM		CHESTER LOAM		WETHERSFIELD LOAM		SASSAFRAS LOAM NO. 1		SASSAFRAS LOAM NO. 2		SASSAFRAS FINE SANDY LOAM	
	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
No magnesium	2.19	1.45	1.75	2.97	2.01	0.84	2.22	0.97	1.75	1.23	3.52	1.05
2 gm. $MgSO_4 \cdot 7H_2O$	2.04	2.04	1.89	3.28	1.78	1.53	1.84	1.93	1.64	1.53	3.00	2.02
4 gm. $MgSO_4 \cdot 7H_2O$	1.68	2.39	1.56	3.51	1.71	1.85	1.67	2.03	1.50	1.91	2.42	2.56

TABLE 6

Influence of magnesium on the percentages of CaO and MgO in carrots grown on different types of soils

Dry matter basis

MAGNESIUM TREATMENT	SASSAFRAS LOAM				PENN SILT LOAM				CHESTER LOAM			
	Roots		Tops		Roots		Tops		Roots		Tops	
	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
No magnesium	.33	.23	2.47	.63	.43	.27	2.46	.60	.49	.29	2.95	.78
2 gm. $MgSO_4 \cdot 7H_2O$	.37	.26	2.25	.84	.38	.27	2.86	.63	.47	.30	2.77	.88
4 gm. $MgSO_4 \cdot 7H_2O$	.35	.32	2.19	.85	.35	.29	2.57	.69	.44	.29	2.79	.94

Lutman and Walbridge (10) note that Japanese millet plants grown with a minimum of magnesium contained about 25 per cent as much magnesium as similar plants grown in a solution carrying an abundance of this element. Scharrer and Schropp (13) say, "Applications of magnesium salts increased the magnesium content of the produce but were accompanied by a decrease in the calcium content."

Sherman (14, p. 240) reports inorganic elements in 150 American dietaries, and these indicate a little more than twice as much magnesium as calcium per 3000 calories.

Wherry (16) reports analyses of six species of plants growing in serpentine

barrens and in nearby Piedmont or Coastal Plain woods. He found when any species invades the magnesian soil of the barrens, there was a marked increase in the MgO content of its ash, although accompanying changes in other constituents show no regularity.

Among the vegetable crops analyzed for CaO and MgO were string beans, garden peas, carrots, beets, radishes, peppers, spinach, and cabbage. Other crops were barley, buckwheat, and soybeans for hay.

TABLE 7

Influence of magnesium on the percentages of CaO and MgO in string beans and cabbage plants grown on different types of soils

Dry matter basis

MAGNESIUM TREATMENT	STRING BEANS ON												CABBAGE PLANTS ON SASSAFRAS FINE SANDY LOAM	
	Sassafras loam				Penn silt loam				Chester loam					
	Beans		Vines		Beans		Vines		Beans		Vines			
	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
No magnesium	1.05	.42	3.93	0.65	1.28	.52	2.07	.51	.95	.51	3.65	.69	2.80	.36
2 gm. $MgSO_4 \cdot 7H_2O$.	1.18	.52	3.96	0.95	1.00	.50	4.13	.70	.98	.53	3.37	.92	2.61	.50
4 gm. $MgSO_4 \cdot 7H_2O$.	1.02	.56	3.76	1.20	0.95	.53	3.99	.78	.92	.57	3.45	.91	2.53	.64

TABLE 8

Influence of magnesium on the percentages of CaO and MgO in radishes grown on different types of soils

Dry Matter Basis

MAGNESIUM TREATMENT	SASSAFRAS LOAM				CHESTER LOAM				DUNELLEN LOAM				WETHERSFIELD LOAM			
	Roots		Tops		Roots		Tops		Roots		Tops		Roots		Tops	
	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
No magnesium	1.26	.36	7.02	.57	1.41	.53	6.92	0.74	1.48	.36	6.28	.28	1.33	.41	6.26	.41
2 gm. $MgSO_4 \cdot 7H_2O$	1.34	.41	6.90	.55	1.50	.64	6.93	0.79	1.36	.46	5.88	.52	1.18	.41	6.38	.53
4 gm. $MgSO_4 \cdot 7H_2O$	1.29	.48	6.68	.77	1.28	.61	7.17	1.01	1.13	.45	6.02	.58	1.20	.47	5.84	.58

Table 5 shows the percentage of CaO and MgO in spinach grown on several types of soil. It will be observed that in nearly every case the percentage of MgO in the plant material is increased with addition of magnesium sulfate. Spinach grown on Sassafras fine sandy loam which received 4 gm. of magnesium sulfate contained nearly two and a half times as much MgO as that grown without magnesium treatment. As was mentioned previously, the percentage of lime decreases as the percentage of magnesia increases. The spinach showed

only slight exception to this for all the types of soil. The type of soil also influences the percentage of magnesium in the plant. For example, on Chester loam without magnesium treatment, the percentage of MgO is 2.97, whereas with the 2- and 4-gm. treatments of magnesium sulfate, the percentages are 3.28 and 3.51 respectively.

Carrots (table 6) show a rather low percentage of CaO in the roots and a high percentage in the tops. The magnesium treatment generally resulted in some increase in the percentage of magnesium in the plant material. In this

TABLE 9

Influence of magnesium on the percentages of CaO and MgO in tomatoes grown on different types of soils

Dry matter basis

MAGNESIUM TREATMENT	SASSAFRAS LOAM				SASSAFRAS SAND				COLLINGTON LOAM			
	Fruit		Vines		Fruit		Vines		Fruit		Vines	
	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
No magnesium	.155	.358	3.09	.45	.131	.253	2.46	.41	.149	.331	2.89	.59
25 gm. $MgSO_4 \cdot 7H_2O$	.136	.315	2.80	.70	.231	.356	2.37	.59	.159	.244	2.91	.63

TABLE 10

Influence of magnesium on the percentages of CaO and MgO in rape and soybean grown on different types of soils

Dry matter basis

MAGNESIUM TREATMENT	RAPE GROWN ON						SOY BEAN HAY GROWN ON					
	Sassafras loam		Sassafras fine sandy loam		Sassafras loam		Penn silt loam		Chester loam		Wethersfield loam	
	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
No magnesium	2.32	.39	3.20	.34	2.00	.63	2.02	.72	1.94	.73	1.97	.66
2 gm. $MgSO_4 \cdot 7H_2O$....	2.18	.45	3.10	.51	**2.01**	.73	2.00	.76	1.82	.75	2.20	.73
4 gm. $MgSO_4 \cdot 7H_2O$ ...	2.27	.54	2.95	.68	1.91	.79	1.93	.81	1.86	.82	2.04	.77

case the type of soil has not greatly influenced the percentage of CaO or MgO.

String beans (table 7) show approximately 1 per cent of CaO and about one-half per cent MgO. The vines are exceptionally high in CaO, some of the sample showing about 4 per cent. The percentage of CaO is high in young cabbage plants (table 7); it decreases with the magnesium treatment, whereas the magnesium increases.

The percentage of CaO in radishes (table 8) does not differ greatly for the different types of soil, the range being from about 1.2 to 1.4 per cent. The

percentage of CaO in the tops is very high, usually above 6 per cent. The magnesium in the plant material tends to increase as the application of magnesium sulfate is increased.

Tomatoes (table 9) show a low percentage of both CaO and MgO in the ripe fruit. The percentage of CaO in the vines is high, varying from about 2.5 to 3 per cent. The magnesium treatment influences the percentage of MgO in the vines more than in the fruit.

Rape and soybeans (table 10) show a rather high percentage of CaO, the highest percentage being noted in rape grown on Sassafras fine sandy loam.

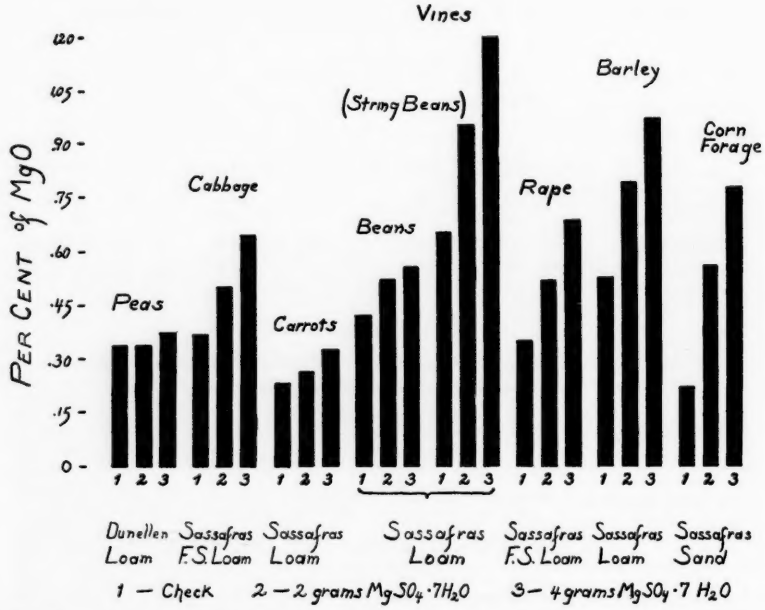

FIG. 3. PERCENTAGE OF MAGNESIUM OXIDE IN SEVERAL CROPS GROWN ON DIFFERENT TYPES OF SOIL, WITH AND WITHOUT MAGNESIUM TREATMENT

Without exception, the percentage of magnesium in the plant material increases with the addition of magnesium sulfate. The percentage of CaO and MgO in barley is low.

Figures 3 to 5 indicate graphically the variations in the percentages of CaO and MgO in the plant material, due to magnesium treatment.

Without undertaking to discuss the significance of increasing the magnesium content of the plant, we may point out that Lutman and Walbridge (10) in their exhaustive study of the role of magnesium in the aging of plants conclude: ". . . magnesium probably plays a secondary part in the senescence of plants.

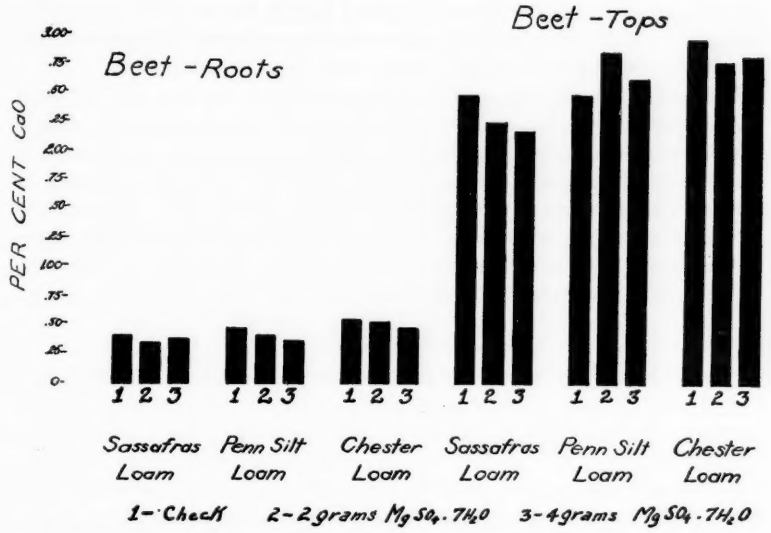

FIG. 4. PERCENTAGE OF CALCIUM OXIDE IN BEETS AND BEET TOPS GROWN ON THREE TYPES OF SOIL, WITH AND WITHOUT MAGNESIUM TREATMENT

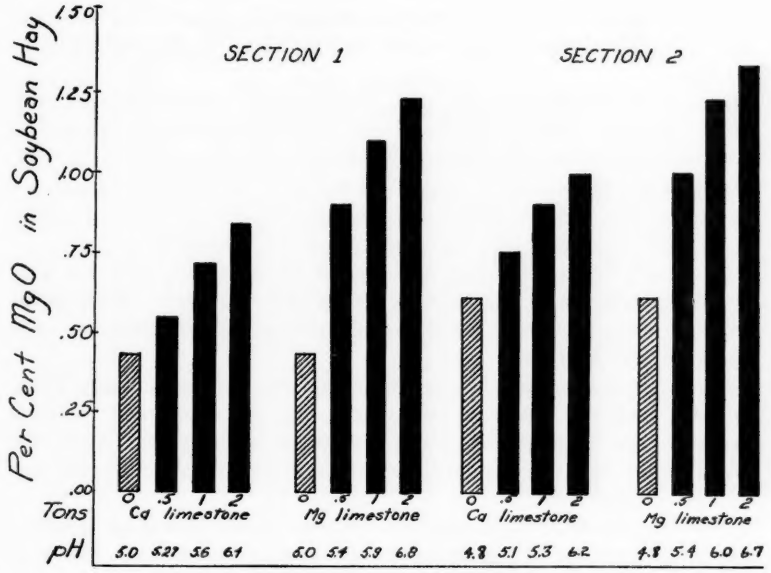

FIG. 5. PERCENTAGE OF MAGNESIUM OXIDE IN SOYBEAN HAY GROWN ON SASSAFRAS LOAM WITH DIFFERENT LIME TREATMENTS

Its lack may be one of the factors concerned therein, but probably many other and more complicated internal disturbances and rearrangements are responsible for all the phenomena associated with normal aging in plants."

Whether or not any importance is to be attached to the fact that the magnesium content of plants may be increased by the use of magnesium sulfate and other magnesium compounds, it is important to remember that the use of magnesium compounds in connection with fertilizer treatment may result in rather wide differences in the magnesium content of the plant. The type of soil, likewise, may be responsible for differences in the CaO and MgO content of the plant. It follows, therefore, that in reporting analyses, it is important, where possible, to state the conditions under which the plants were grown.

SUMMARY

Numerous analyses have shown that the soils of New Jersey, with the exception of some of the very sandy areas, contain a rather high percentage of magnesium. Chemical analysis, however, does not answer the question as to whether there may be considerable areas of farm land in the state where the supply of available magnesium is not enough for normal crop growth. Work was started, therefore, about three years ago for the purpose of gaining further information along this line.

A variety of vegetable crops, mixed hay, soybean hay, and corn forage were grown on several types of soil without magnesium treatment and also with magnesium sulfate or dolomitic limestone treatment. A part of the work was done in the greenhouse, a part in small wooden forms outside, and a part in the field.

Some of the vegetable crops gave definite increases in yield when magnesium sulfate was used. With a number of the crops the increases were negligible. In all the experiments, there were probably about as many decreases in yield as there were increases where magnesium sulfate was used. In one instance the decrease was sufficient to indicate magnesium deficiency. Such decreases as are noted more likely represent negative results or are incidental.

Tomatoes grown on Sassafras sand and on Sassafras and Collington loam gave definite increases when magnesium sulfate was used. String beans and corn forage grown on Sassafras sand gave fair increases with the magnesium sulfate treatment.

Mixed hay and soybean hay grown on field plots (Sassafras loam) where dolomitic limestone has been used over a long period, showed moderate increases when compared with yields from corresponding plots treated with calcium limestone (the calcium limestone, however, contained a small percentage of magnesium).

There is very little indication that the soils of northern New Jersey in general are deficient in magnesium for the crops to be grown. The work reported here gives some indication that certain of the soils of southern New Jersey may be deficient in magnesium for some crops.

Analysis of the plant material for CaO and MgO has shown very definitely that with applications of magnesium sulfate, the magnesium content of the plant is commonly increased to a point considerably above that of plants grown under similar conditions but without applications of magnesium. In some cases the increase was more than 100 per cent.

In a number of the crops, the CaO tends to decrease as the MgO increases.

Attention is directed to the fact that when studies are being made on the composition of plant material, it is important to know the type of soil and the fertilizer and liming practices followed in the growing of the crop.

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PLATE 1. STRING BEANS GROWN IN SASSAFRAS SAND

Left, with magnesium sulfate; right, without magnesium sulfate. Note the rough, abnormal appearance of the leaves, the slender stem, and the scarcity of nodules on the plant without magnesium.

PLATE 1

STUDIES IN THE ELECTRODIALYSIS OF SOILS: V. BACK TITRATION CURVES OF SOILS AND HUMATES

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Titration curves of soils are easily determined by shaking known weights of the base-free soils with increasing amounts of alkali for 48 hours and finding the pH values.[1] Back titration curves could be determined by adding increasing amounts of acid to known weights of fully saturated soil, but this procedure involves the accumulation of increasing amounts of a soluble salt which is bound to affect the reaction.[2] Electrodialysis, on the other hand, appears to be free from this objection, and therefore the base could be gradually removed and the pH value determined at every step. If such a procedure proved feasible, electrodialysis would be a much more useful method of study than any hitherto available for this purpose. The object of this investigation was to explore these possibilities.

EXPERIMENTAL

The application of the rotating anode to the electrodialysis of soils has already been described.[3] In the apparatus devised for the purpose, the principle of electrofiltration was applied, and the electrodialyzate was continuously removed and collected. This apparatus proved satisfactory for soils but was slightly modified for humates (fig. 1). Parchment paper was supported on hardened filter paper (Whatman 50), since the latter, alone, allows ready passage of humates, but, as a support, ensures against leakage of humus through pinholes which sometimes develop in parchment papers. Good filter paper impregnated with collodion was found as satisfactory as parchment paper. The glass vessel in which the electrodialyzate was collected was an ordinary Erlenmeyer flask with the bottom knocked off. The dialyzate was collected at definite intervals by opening the stopcock and was replaced by fresh water. Current was taken from a 220-volt main and kept exactly at 0.1 ampere through a suitable resistance. The temperature did not rise above 32°C.

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Electrodialysis of soils

The single-base soils used in this study were prepared from a black cotton soil of high base-exchange capacity. This soil contained about 5 per cent humus, which was destroyed by alkaline permanganate. As humus has been studied separately in this paper, this procedure was considered necessary to get a clear idea as to the behavior of each. After the destruction of humus, the soil was acid-treated and neutralized with different bases. All pH values were determined with the glass electrode. Na-soil was prepared by neutralizing the H-soil to different pH values, and the back titration curves were

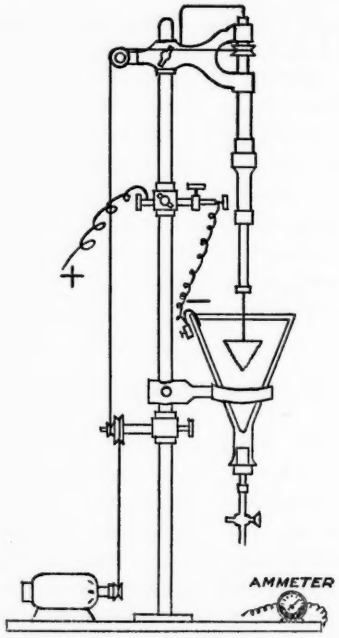

FIG. 1. APPARATUS USED FOR THE ELECTRODIALYSIS OF HUMATES

determined in every instance. In the case of other bases, only the highest pH value was taken. Five grams of each soil was used for electrodialysis. The results are plotted in figure 2 along with the forward titration curves of the H-soil. The remarkable difference in the forward and back titration curve is difficult to explain. It is seen that whatever the initial pH of the Na-soil, it falls rapidly to approximately that of the H-soil even when only 50 per cent of the base has been removed by electrodialysis. Further removal of the base produces but little effect on the pH value. This behavior is shown in a more striking manner where divalent bases are involved, especially with

Mg-soil, in which the pH drops to the lowest value when hardly 40 per cent of the base is removed by electrodialysis.

Electrodialyzed soil has frequently formed the material of study by various workers when a completely unsaturated or H-soil was required. The ultimate pH value or the reaction of the electrodialyzed soil has also acquired a certain amount of physical significance in soil literature. These results seem to show that unless electrodialysis is carried on for a very long time and proper care

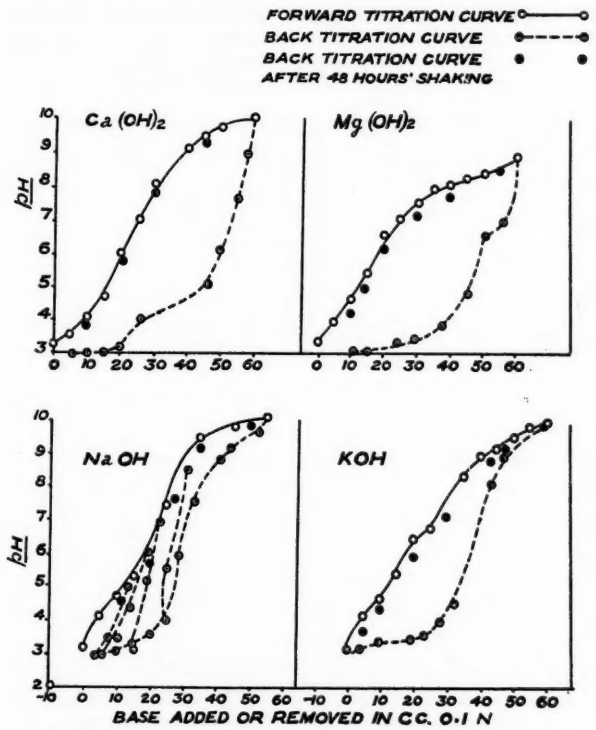

FIG. 2. FORWARD AND BACK TITRATION CURVES OF SOILS

is taken to watch the course of the reaction, this method of preparing unsaturated soils may easily lead to erroneous conclusions. Dilute-acid treatment for producing base-free soils, which has been adopted throughout these studies, is not only quicker but more reliable.

The enormous difference in the forward and back titration curves was baffling until the following reasoning was applied: when alkali is shaken with soil, at least 48 hours is required for attainment of equilibrium; therefore, if alkali is removed from the soil, an equally long time must elapse before

equilibrium can be established. The soil suspension was, therefore, shaken for 48 hours after each incremental removal of alkali, and the pH value was determined after shaking. The back titration curve thus obtained very nearly coincides with the forward curve.

The mechanism of pH changes in the soil due to the addition or removal of alkali may be visualized somewhat as follows: The complex ferroaluminosilicates which are mainly responsible for the acidoid character of the clay

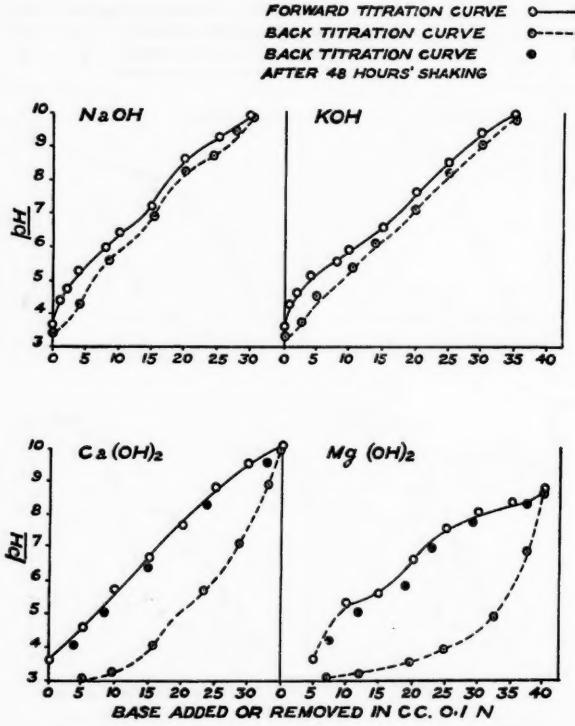

FIG. 3. FORWARD AND BACK TITRATION CURVES OF HUMATES

do not exist as individual molecules but as compound particles, the molecular forces of cohesion resulting in a stable structure which is not broken down in ordinary mechanical analysis. When alkali is added to these compound particles, the molecules near the surface are neutralized to a much greater extent than are those toward the inside. The pH registered is, therefore, too high, and it gradually adjusts itself to a lower value on shaking. On the other hand, when alkali is removed from the soil, it comes mostly from the surface molecules. The pH registered is, then, too low, and it gradually

rises as the alkali from the inner molecules slowly diffuses out. This view, if correct, leads to a very important conclusion, namely, that exchangeable ions are diffusible, and the establishment of equilibrium leads to a uniform distribution of the exchangeable ions throughout the soil mass. It follows also that if this equilibrium is disturbed by the removal of ions from one portion, it must lead to the migration of ions. In other words, if plants make use of the exchangeable bases from the part of the soil in immediate contact with the root hairs, more of these bases must travel from other parts to make up the deficiency. Exchangeable bases, therefore, can behave like soluble salts in this respect.

Electrodialysis of humates

Humates of Na, K, Ca, and Mg were prepared by the addition of equivalent amounts of alkalies followed by shaking for 48 hours. In one set of experiments alkali was removed continuously, and the pH value of the alkali removed was determined at definite intervals. Ca- and Mg-humates, like the soil suspensions, were also shaken for 48 hours after every removal of alkali. In every case, 0.5 gm. of humus was taken for electrodialysis. The forward and the back titration curves are given in figure 3. The general similarity between the soil and the humus curves is at once apparent. Likewise the back titration curves are identical to the forward curves, provided sufficient time is allowed for attainment of equilibrium after the removal of any portion of the alkali. It is to be noted that Na- and K-humates show only a very slight shift of the back titration curves even without shaking. This is in conformity with the view that humates of alkali metals are soluble in water.

It is convenient at this juncture to point out that a part of the alkali, especially the Ca and Mg, displaced by electrodialysis, sticks to the cathode and must be removed by acid treatment every time the alkali is determined. Simple titration of the electrodialyzate may lead to very erroneous results. For instance, as little as 10 per cent of the Mg may come down in the electrodialyzate, the rest sticking to the cathode. The exact mechanism of this deposition of bases on the electrode is under investigation. In the meantime, the importance of taking account of this portion of the electrodialyzed bases must not be overlooked.

SUMMARY

Back titration curves of single-base soils and humates were determined by electrodialysis. These curves are identical to forward curves, provided the suspension is shaken for 48 hours after every incremental removal of alkali.

MEETINGS OF THE THIRD COMMISSION OF THE INTERNATIONAL SOCIETY OF SOIL SCIENCE

The Third Commission of the International Society of Soil Science, concerned with the subject of soil microbiology, will hold meetings in New Brunswick, N. J., from August 30 through September 1 on the campus of the New Jersey Agricultural Experiment Station and Rutgers University. Papers will be presented on three subjects: Legumes and Legume Bacteria; Microbiology of Soil Organic Matter; and Azotobacter and Its Significance in Soil Processes.

The program on August 30 will deal with the subject Legumes and Legume Bacteria, on which reports will be given by the following members: W. A. Albrecht, University of Missouri; F. E. Allison, U. S. Department of Agriculture, Washington, D. C.; A. Demolon, Centre National de Recherches Agronomiques, Versailles, France; J. Dufrenoy, Université de Bordeaux, France; H. Katznelson, New Jersey Agricultural Experiment Station; L. T. Leonard, U. S. Department of Agriculture, Washington, D. C.; K. V. Thimann, Harvard University; H. G. Thornton (President of the Commission), Rothamsted Experimental Station, England; W. W. Umbreit and P. W. Wilson, University of Wisconsin; A. I. Virtanen, Biochemical Institute, Finland; A. L. Whiting, The Urbana Laboratories, Urbana, Ill.

The subject of Microbiology of Soil Organic Matter will be discussed by the following members on the morning of August 31: Chr. Barthel and N. Bengtsson, Lantbrukshögskolan, Sweden; F. E. Clark and Charles Thom, U. S. Department of Agriculture, Washington, D. C.; D. Fehér, Institute of Forestry, Hungary; H. Murata, Kogoshima Imperial College of Agriculture and Forestry, Japan; A. G. Norman, Iowa State College; C. E. Skinner, University of Minnesota; S. C. Vandecaveye, Washington State College; S. A. Waksman, New Jersey Agricultural Experimental Station; J. Marszewska-Ziemiecka, The National Institute for Agricultural Research, Poland.

During the afternoon of August 31, papers will be presented on the subject Azotobacter and Its Significance in Soil Processes by the following members: G. Guittonneau, Institut National Agronomique, France; C. K. Horner and Dean Burk, U. S. Department of Agriculture, Washington, D. C.; H. W. Reuszer, Colorado Agricultural Experimental Station; R. L. Starkey, New Jersey Agricultural Experiment Station; M. Winnik and M. Goldberg, Mikveh-Israel Experimental Station, Palestine. A conference will be held on legume inoculants under the direction of A. W. Hofer, of the New York (Geneva) Agricultural Experimental Station.

Following the meetings, on September 1, an excursion will be made to some of the agricultural regions of New Jersey.

The meetings will be held in close cooperation with the Third International Congress for Microbiology, which is to be officially opened on September 2. Anyone wishing information concerning the program and arrangements during the period of the meeting should communicate with R. L. Starkey, Agricultural Experiment Station, New Brunswick, New Jersey.